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THERMAL PERFORMANCE EVALUATION OF THE INFRARED TELESCOPE DEWAR SUBSYSTEM

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By Eugene W. Urban

Space Science Laboratory
Science and Engineering Directorate

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16. ABSTRACT

A series of seven thermal performance tests were conducted with the superfluid helium dewar of the Infrared Telescope Experiment from November 1981 to August 1982. Test objectives included measuring key operating parameters, simulating operations with an attached instrument cryostat, and validating servicing, operating, and safety procedures. This report is a comprehensive summary of all test activities and results.

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ABBREVIATIONS

DAS	Data Acquisition System
DSS	Dewar Subsystem
FIRSSE	Far Infrared Sky Survey Experiment
FR	Fill Receptacle
FSS	Flight Support Structure
GSE	Ground Support Equipment
IRAS	Infrared Astronomical Satellite
IRT	Infrared Telescope
IVCS	Inner VCS
LHe	Normal Liquid Helium, $4.2\ K \leq T \leq 2.17\ K$
MVCS	Middle VCS
OVCS	Outer VCS
RSS	Rotation Support Structure
SD	Supply Dewar
SFHE	JPL Superfluid Helium Experiment on Spacelab 2
SHe	Superfluid Liquid Helium, $T < 2.17\ K$
TA	Transfer Assembly
TAO	Thermoacoustic Oscillations
TPE	Thermal Performance Evaluation
TSS	Transportation Support Structure
UAH	University of Alabama in Huntsville
VCS	Vapor-Cooled Shield
VMA	Vacuum Maintenance Assembly
VR	Vent Receptacle

TECHNICAL MEMORANDUM

THERMAL PERFORMANCE EVALUATION OF THE INFRARED TELESCOPE DEWAR SUBSYSTEM

I. Introduction

This report summarizes the objectives, chronology, and results of the series of cryogenic thermal performance evaluation (TPE) tests conducted on the Infrared Telescope (IRT) Dewar Subsystem (DSS) from November 1981 to August 1982. Seven distinct cold test sequences were performed, each of which was intended to satisfy several of the general TPE objectives. Only one test failed to yield much useful data. All test objectives were satisfied except for those involving the transfer of low pressure liquid helium (LHe) from a supply dewar into the DSS.

II. General

The cryogenic TPE's were performed on the Dewar Subsystem in order to understand as completely as possible the operation of the entire subsystem and the cryogenic ground support equipment (GSE). Steady state operating conditions (temperature, pressures, flow rates, etc.) of the cryogenic apparatus had been predicted analytically, but it was recognized that the uncertainties in the predicted parameters were large. On-orbit operations and scheduling of infrared observations will depend crucially on accurate knowledge of these factors. We must understand how rapidly the system can move from one steady state to another. It was also not know how well the GSE would perform or how long the servicing operations would take. This information is required in order to plan for conducting pre-launch servicing while other STS operations are in progress, particularly since experiment fill and topoff on the launch pad is now required.

The seven DSS TPE's, numbered I through VII, were conducted basically according to the Procedure for Thermal Performance Evaluation (TPE) of the Infrared Telescope Dewar Subsystem, IRT-316, dated October 1981. The procedure contains a discussion of the test objectives, GSE, special operational considerations, and a thorough description of the safety aspects of the DSS and of the TPE operations. Because several modifications to the flight hardware, the GSE, and the original procedure were made during the course of the several tests, the permanent detailed record of the tests consists of the as-run procedure, the data record sheets, and the printouts from the Data Acquisition System (DAS). A chronological summary of the TPE's is given in Table 1.

TPE's I and II were conducted with the DSS mounted upright in a fixed work table. In the remaining TPE's the DSS was mounted in the Flight Support Structure (FSS) attached to the GSE Transportation Support Structure (white pallet simulator) which in turn was mounted in the GSE Rotation Support Structure (RSS). TPE III in the upright attitude yielded only data on LHe filling and warmup. TPE IV was also conducted in the upright attitude in order to complete tests from the preceding TPE's. TPE's V, VI, and VII were conducted primarily in tilted attitudes.

In the reports of the individual TPE sequences which are presented below, the specific test objectives will be identified by number from the complete list of objectives for the entire dewar TPE series given in Table 2. Table 3 summarizes the TPE's in which the objectives were accomplished.

A schematic of the dewar subsystem at the start of TPE I is shown in Figure 1, while Figure 2 is a photograph of the system at the same time. The configuration of the DSS itself was changed on several occasions. These changes are noted in the summaries that follow. The configuration of the GSE was also changed several times. Some of the changes resulted from routine activities such as connecting and removing supply dewars and transfer lines, and may have occurred several times during a single TPE. Schematics of these configurations can be found in the as-run procedure. Other GSE changes remained in place throughout a TPE, and are noted in the summaries.

III. TPE I

The first cooldown of the IRT dewar subsystem was begun on November 6, 1981, 2 days after completion of the final leak check of the Transfer Assembly (TA) dome. The DSS was in a work table, and GSE fill and vent lines LX and L4B, respectively, were connected, as shown in Figure 3. Two vacuum gauges, PV1 and PV2 a pressure gauge, PV3, and a relief valve, RV, were attached to the dewar vent line connection to provide pressure measurements and relief capability.

A simplified DAS without voltage conversion to engineering units and without hard copy printout was in place for this first test. Instead, continuous visual monitoring of T1, T2, LL and PV1,2,3 was done with frequent written recording. Thermometers T5 and T6 were in three-wire and two-wire configurations, respectively; their outputs were not accurate.

The test objectives intended to be accomplished in this TPE were 1, 3, 4, 5 and 10 (see Table 2). Those objectives actually accomplished were 1, 3 (partial), 4a, 5, and 10a (see Table 3).

A graphical summary chart of TPE I is shown in Figure 4 and an index of major events is given in Table 4. This TPE had essentially five significant subsections which are each treated in detail below.

A. Initial Fill Operations

LHe flow from a full 100 ℓ supply dewar (SD) via LX began at 0900 on 11/16 or 11/16:0900, and T1 and T2 began to cool. SD pressure was maintained at approximately 6 psig by an external GHe supply and regulator. Very soon the dip tube of LX began to frost and its entire surface was quite cool. A second full SD was connected at 1255. At 1338 T1 reached 22 K and began to oscillate with a period of a few seconds and an amplitude of $\sim$ 2 K, indicating that small bursts of liquid were entering the dewar and quickly evaporating. T1 reached a minimum value of 9.4 K at 1351 and began to increase. Reduction in the SD pressure only resulted in a reduced flow and more rapid warming of T1. A third full SD was connected at 1450, but at 1500 the excessive frosting on LX led us to terminate the transfer.

The system was left closed off with relief valves on L4B over the weekend. The following Monday (November 9) LX was reevacuated and leak checked. It had no detectable leak suggesting that the line was thermally inefficient, particularly the dip tube.

At 11/10:1230 a second cooldown was attempted with a full SD. SD pressure was held at 4.5-5.0 psig. T1 reached a minimum of 15 K at 1445 accompanied by oscillations. LX frosted again. The test was terminated at 1500.

At 11/16:1200 a third transfer was begun using a full 500 ℓ SD which was maintained at 4.8-4.9 psig. From 1400 to 1430 SD pressure was gradually raised to 7.6 psig. T1 reached a minimum of 13 K with oscillations at 1420 and then warmed. SD pressure was reduced to 5 psig.

A telephone call was made to Mr. Wickstrom at Ball Aerospace, Boulder, to find out what their experience had been in transferring into Infrared Astronomical Satellite (IRAS), Far Infrared Sky Survey Experiment (FIRSSE), and Superfluid Helium Experiment (SFHE) experiments. He stated that they had had to transfer at SD pressures as high as 10 psig.

We raised the SD pressure from 5.0 to 10.0 psig between 1500 and 1530 and only succeeded in further warming T1. LX was icing heavily. We attempted to increase the flow by pumping on the vent line. Flow was so high that one of the two GSE vacuum pumps on L4 stalled out but there was no improvement. Bypassing flow through the TA plumbing by opening V17 had little effect on the flows or temperatures. At 1730 this test was terminated.

It was decided that LX would not be used further and that the bayonet on a standard short laboratory transfer line containing a bayonet disconnect and a shutoff valve could be adapted to mate with the long bayonet fill receptacle (FR) on the TA. University of Alabama in Huntsville (UAH) designed and made a stainless steel adapter in a few hours. Figure 5 is a photograph made some time later which shows the laboratory transfer line LX' installed in FR. This figure also shows the location of the vacuum and pressure gauges and the other apparatus used in these tests.

The fourth transfer was started at 11/17:1400 using LX'. SD pressure was held below 4.4 psig. The vapor-cooled shields (VCS) were still very cold from the previous day's transferring. At 1459 liquid collection began as indicated by both LL and the fact that PV3 dropped from more that 1 psig to less than 0.4 psig. During liquid flow the SD pressure was held at about 6.4 psig to hasten the transfer. At 1541 the liquid volume indicated 124 ℓ in the dewar. The SD was empty at this point as indicated by a drop in the SD pressure and a gradual decrease in LL. Transferring was stopped. When disturbances had time to settle out at 1602, the LL indicated a 57.5% level, which was interpreted at the time to be 129 ℓ. Calibration of LL in TPE II when the superfluid (SHe) fully evaporated showed that 57.5% corresponded to 147 ℓ!

During the preceding tests V6 and, to a slight extent, V13 became more difficult to close. It was seen later that the main closure threads were galled. When the filling operation was done it was not possible to close V6 at all, so the valve on LX' was closed to stop the flow.

While this transfer was in progress the DAS was brought on line to record T1-T6 and LL. This capability was maintained from this time on and several more parameters were added later.

B. Stabilization and Performance with LHe

With the LHe volume at 147 ℓ at 11/17:1600 we allowed the DSS to begin to stabilize thermally so that steady state performance could be measured. With the internal pressure essentially at atmospheric, LX' could be removed from FR without ingestion of air/water vapor. On November 18 V15(RV4) was

installed and locked in place. L4B remained in place in VR and a flow meter F1 was attached to its outboard end to measure the boiloff. There was no pressure control on the vent system, nor did we regularly record the atmospheric pressure. A schematic of the system during the stabilization period is shown in Figure 6. Both oil- and water-filled wet test meters and Hastings-Raydist mass flow meters were used and cross compared November 18-24. Connecting and disconnecting flow meters affected the plumbing impedance and temporarily perturbed the flow rates. Flow values given in Figure 4 were taken after perturbations had settled out.

Because the VCS had supercooled during the high flow filling operations, we expected that a period of several days might be required for the shields to reach their steady state temperatures and for the heat flux into the LHe and the resulting vent flow rate to stabilize. Figure 4 shows that the inner VCS (T2) required essentially 10 days to reach its steady state temperature of 24 K, having gone through a single, highly damped oscillation cycle. The middle (T3) and outer (T4) VCS required 13 and more than 13 days, respectively, to stabilize at their final temperatures of 74 K and approximately 155 K.

Since the heat load and mass flow rate ($\dot{m}$) should be dictated almost entirely by T2, F1 = $\dot{m}$ should have behaved as did T2. However F1 rose monotonically from a minimum on November 18, when first flow readings were taken, until November 26 and exhibited a fairly large drift, even after T2 had become constant on November 27. We later interpreted this result to be due to weak thermoacoustic oscillations in the fill or vent lines, or both.

As F1 rose from 6 mg/s to its final value of approximately 11.5 mg/s, the rate of decrease of LL increased and then became constant. During the period November 28-December 1 LL fell at an average rate of 0.34 liter/hr. With an LHe density of 125 g/ℓ, a heat of vaporization of 20.6 J/g, and correcting for the fact that 15% of the evaporating mass remains in the dewar to fill the volume formerly occupied by the vaporized normal liquid, we found that 0.34 ℓ/hr evaporation rate corresponded to a heat load of 243 mW and a vent mass flow rate of 10.0 mg/s.

Throughout the stabilization period the liquid temperature remained at 4.2 K. Since we did not control the internal pressure and the atmospheric pressure probably changed considerably during the TPE, temperature and flow rate drifts were expected to occur.

C. First Conversion to SHe

Our plan for the first conversion of the DSS to superfluid helium required that only approximately 20 liters of fluid would remain in the vessel at the transition. This would insure that if there were a superleak in the lower part of the vessel, a resultant loss of guard vacuum would not lead to heating and pressurization of more than a small amount of mass. On December 1 when the system appeared to have reached a steady state, we interpreted the LL reading as indicating that 30 liters of LHe remained in the dewar. With the expected 40% mass loss due to evaporative cooling, we anticipated that if we converted to SHe from this state, we would reach the lambda transition with approximately 18 liters of SHe. Consequently we set up the GSE for pumpdown to SHe. As it later turned out when the LL instrument zero was corrected, the volume of LHe at this time was 50.5 liters.

At 12/01:1040 the system was in the configuration shown in Figure 7. The roughing pump RP1 was started, SV opened, and MV opened to begin the conversion. High flow rates of cold vapor during the initial phases of the conversion required that MV be open only slightly at the beginning to prevent cooling of the pump oil and stalling of the pump. Therefore MV was opened only gradually, reaching the full open position when the liquid was near the transition.

During the conversion process, and particularly near the lambda point when the thermal conductivity of the LHe is poor, the LL gauge does not work properly. Furthermore it produces heat in the fluid, increasing the required pumping load slightly. Consequently LL was deactivated until the system pressure reached about 40 torr (the pressure at T_λ is 38 torr). The liquid passed through the transition at 1309 hrs as evidenced by:
(1) T1 = 2.17 K; (2) LL again began to register; and (3) PV and T1 began to fall again more rapidly after a plateau of several minutes caused by the poor thermal conductivity of the liquid just above T_λ and the very large liquid specific heat peak at T_λ. LL read somewhat low for several minutes, but at 1318 it indicated 11% which was later interpreted to mean 31 liters. Consequently we see that the conversion from 50.5 to 31 liters was accomplished at an efficiency of 61%, which is quite satisfactory.

Since there was no indication of a superleak in the dewar vessel, we continued pumping to attempt to reach 1.7 K or less. At 1610 T1 reached 1.729 K. A few minutes later after MV had been momentarily closed, the vent line was found to be blocked somewhere within the dewar, as evidenced by the rapid decrease of PV1 to a low value, while T1 began to increase slowly.

D. Vent Line Blockage

In general, blockage of a dewar vent line is potentially a very serious problem. If not cleared or bypassed, it can lead to a over pressurization rupture of a dewar. Our situation was never dangerous, even though it was clear that some malfunction had occurred. The evidence indicated that air had leaked into the low pressure vent plumbing and had been drawn deep into the cold sections of the plumbing where it froze, gradually filling the line until the blockage was complete. Our immediate response was to shut SV and MV and turn off RP1, then pressurize the vent circuit with gaseous helium (GHe) to the 3 psig relief valve pressure to prevent any further ingestion of air or water vapor.

With the internal plumbing pressure at about 10 torr absolute and increasing very slowly, it would take many hours for the pressure to rise to one atmosphere and many more for the pressure to become dangerous. We decided, therefore, to leave the system alone for several hours and to monitor the liquid helium temperature T1 which provided an unambiguous and accurate indication of the internal pressure. If the vent blockage did not clear itself, then when the internal pressure reached ambient, we would open the fill circuit and vent the system through that path.

From 1610 to 2240 the internal pressure rose from 9.6 to 15.6 torr absolute (1 torr/hr). With no vent flow to cool them, the VCS warmed. At 2240 T2, T3 and T4 had warmed to 34.2, 60.9 and 125.8 K, respectively. At this time T1, which had been warming at about 1 mK/min, suddenly began to warm at $\sim$3 mK/min, indicating that external GHe was beginning to flow past the blockage and pressurize the liquid helium. At 2320 the heating rate of T1 abruptly increased to 20 mK/min. Obviously the blockage had opened up.

The freezing temperatures of nitrogen and oxygen (at one atmosphere pressure) are 63.2 and 54.8 K respectively. It appears probable that the blockage was primarily nitrogen which had frozen in the small diameter vent connection between the outer and middle VCS which were at about 87 and 40 K, respectively, when the blockage occurred. Then as the middle VCS warmed through 61 K, the connecting tube was slightly warmer and the frozen nitrogen melted out, opening the line. Of course the contaminants, including water vapor, remained within the plumbing, so we decided to completely warm and repump the system and to correct the problem which permitted the air ingestion.

Air apparently leaked into the low pressure vent system at four locations listed below:

1. One small leak at a connection at the outboard end of the GSE vent line. Because it was small, remote from the dewar and near the pump, it probably did not contribute to the blockage. This leak was sealed when found.

2. A major leak past the rubber O-ring which sealed the vent bayonet probe VP on L4B into the vent bayonet receptacle VR on the TA. This leak resulted from a slight incompatibility of the male and female bayonet components. As a result the sealing O-ring was improperly compressed and it leaked when it became moderately cold.

3. A major leak past the vent valve (V13) shaft gland. This valve had been employed in its original configuration which was for use with pressurized cryogens inside of the plumbing, not low pressure. Consequently air was able to move past the chevron seals and into the plumbing.

4. A similar major leak in the fill valve (V6) shaft gland.

E. Warmup

It is of some interest to consider the warmup process of the DSS. We may wish at some future time not only to warm the system rapidly for a repair, but for prelaunch cryogenic servicing. Therefore, we need to know how slowly the dewar will warm after the last liquid has evaporated. Two conclusions which can be drawn from observing T2, the inner vapor cooled shield temperature, during several warmups are:

1. Without active assistance (purge) T2 will require about 100 hrs to warm from about 50 to 150 K and an additional 110 hrs to reach 250 K.

2. With a warm GHe purge the warmup time for T2 from 50 to 150 K can be reduced to less than 24 hrs.

F. TPE I Conclusions

At the end of TPE I the following conclusions could be drawn:

1. The DSS can be safely filled and operated with normal LHe while in the upright attitude.

2. The DSS can be safely converted from LHe to and operated with at least a small amount of SHe in the upright attitude.

3. Careful procedures and hardware verification are required to prevent ingestion of and vent blockage by air and water vapor.

4. When vent line freeze blockage does occur, the system is very forgiving and a safety hazard does not immediately result. By pressurizing the plumbing with GHe to a positive pressure, air/water vapor ingestion can be stopped. The liquid helium temperature rise is so slow and the VCS temperature rise in the absence of vent flow is so fast that the frozen blockage will melt and clear the vent path, long before the internal pressure becomes high enough to constitute a safety hazard.

5. The DSS steady state performance with LHe is satisfactory and has no unexplained features. Steady state vent flow rate was 12.0 mg/s representing a liquid evaporation rate of 14.1 mg/s or 9.8 liters/day. This corresponds to a total heat load to the liquid of 228 mW. Storage efficiency was 3.9%/day compared with quoted efficiencies of about 1.5%/day for unmodified 250 liter commercial storage dewars. If the flight dewar were in a stand-alone operation (not cooling the flight cryostat), 125 liters of LHe would last 12.8 days. As discussed later, we suspect that thermoacoustic oscillations (TAO) occur in the dewar plumbing when the liquid is at 4.2 K and ambient pressure, introducing additional heat into the dewar.

6. The flight sensors and data acquisition system operated satisfactorily. Since the DSS was upright, T5 and T6 on the porous plug did not cool enough to give meaningful readings.

IV. TPE II

Following the air ingestion problems and the galling of V6 and V13 stems, several hardware and procedure modifications were made prior to the start of TPE II. The general modifications for this TPE included: (1) Temporary removal of the stem assemblies from V6 and V13 for repair; (2) installation of vacuum sealed caps to V6 and V13 stem housings to permit safe low-pressure operation; and (3) addition of an extended pumping line, valves, and pump to the vent line termination to permit normal-to-superfluid conversion and SHe testing with V16(RV3) installed (necessitated by inoperative V13).

TPE II, which ran from December 28, 1981, to January 15, 1982, was done in two phases. Figures 8 and 9 summarize the configuration and results of the first phase, while Figures 10 and 11 cover the second phase. Table 5 is an index of major events. The DSS was upright in the fixed work table. Filling was via the

short laboratory transfer line LX'. Test objectives to be accomplished were 1b, 3, 4, 5, 10b, 12, 13, 14 and 15. Objectives 12 and 15 were only partially completed.

A. LHe Fill

LHe transfer began at 0900 on December 23 from a partially full 500 liter SD. None of the problems of TPE I were encountered. In fact cooldown was faster than desired and liquid collection began at 1015. About 24 liters was collected and the transfer was stopped; the LHe boiled away by 1230 at which time transfer was again started. The first 500 ℓ SD was empty at 1345 with 167 ℓ in the DSS. A new 100 ℓ dewar was connected. About 7 ℓ was lost during the changeover. The DSS was filled to 232 ℓ at 1500, LX' was removed and a 3-psig relief valve was installed on the outboard end of L4B.

By 12/24:0800 the dewar had pressurized to 922 torr absolute (3 psig), and a pressure oscillation was observed on PV2. Due to the nature of the gauge mechanism, amplitude and period could not be accurately measured but appeared to be about 2 torr peak-to-peak at 2 Hz. The dewar was slowly depressurized to ambient, and a 5000 standard cubic centimeters/minute (sccm) (21.3 mg/s GHe) Hastings-Raydist flow meter was attached to the vent line exit. The system was left alone until 12/28:1300. During this time the flow rate exceeded the range of the flow meter, and the liquid level fell at an average rate of 0.57 liters per hour or 13.6 liters per day; this corresponds to a normal fluid evaporation of 19.8 mg/s and a heat load to the helium of 404 mW. Note that so long as the fluid is near or below the lambda point, cold gas density is so low that liquid boiloff rate equals vent mass flow rate, but that at 4.2 K and ambient pressure, as in the present case, 15% of evaporating liquid must remain in the dewar as high density gas. Consequently 19.8 mg/s LHe evaporation results in 16.8 mg/s vent flow rate.

The observed vent pressure oscillations, which clearly were classical TAO, may be an inherent property of the DSS plumbing configuration, but probably contributed little to the boiloff measured in TPE I; they were not observed and the steady state vent flow rate was only about 11.5 mg/s (2700 sccm N_2 equivalent). It is likely that the temporary hardware modifications made for TPE II enhanced the TAO driving mechanisms. An extra long vent line and the dead end, warm standpipes of the capped V6 and V13 stem housings probably improved the conditions for resonance. It was expected that conversion to low pressure and low gas density of the superfluid phase would reduce the TAO's. Conversion did, in fact, eliminate the TAO's.

B. Conversion to SHe

Conversion began at 1300 on December 28 with 97 liters in the dewar and, by adjustment of the roughing pump (RP) inlet manual valve (MV), was kept slow enough to prevent pump shutdown. It was possible to open MV fully at 1430 when the LHe temperature was 3.1 K. T_λ was reached at 1700 with 55 ℓ remaining. Conversion loss was 43%.

C. Stabilization and Performance with SHe

Except for the addition of flow meters to the outlet of the RP, no changes were made to the system until January 15 when at 1200 the last SHe evaporated. As shown in Figure 9, the VCS temperatures and flow rate required several days to reach steady state. During the high flow rates of the conversion process the VCS's were supercooled, the inner shield reaching a minimum temperature of 5 K before beginning to warm. The inner, middle, and outer VCS required approximately 5 1/2, 10, and 7 days, respectively, to stabilize at their final temperatures of 36, 100, and 185 K. The flow rate F1 went through a minimum of 3.6 mg/s at 24 hours and then took about 9 days to stabilize at 8.4 mg/s. The corresponding slope of the liquid level curve represents a boiloff rate of 8.0 mg/s, agreeing with F1 to within 4.8%. This confirms the essential validity of determining system performance from the steady state flow rate. A boiloff of 8.0 mg/s equals 4.75 liters per day or 1.9% per day which compared favorably with the 1.25-1.5% per day boiloff of unmodified commercial LHe storage dewars. If the IRT dewar, half full of SHe (125 ℓ), could operate as a stand-alone storage container, the lifetime would be 26.3 days.

Following the initial rapid fluid cooling during conversion, T1 went through a broad minimum at 1.619 K from 1400 to 1800 on December 29 and then rose slowly. It reached 1.750 K on January 5 and remained between 1.745 K and 1.758 K until the minute the last fluid evaporated on January 15. We allowed the SHe to completely evaporate in order to calibrate the depth probe zero position and to see how the system would behave upon going dry. When the last liquid was gone, F1 increased by a factor of 3 over a half hour, cooling the VCS somewhat. F1 then decreased for 2 hrs to zero and the VCS began to warm rapidly. The inner vapor cooled shield (IVCS) initial warming rate was 3 K/hr and gradually decreased. Warming continued for 3 days until the second part of TPE II began.

Several factors contribute to the improved DSS performance when operated with SHe. These factors include greater fluid density, greater heat of vaporization, lower relative density of cold gas and fluid, and others. Details are given in Appendix A.

D. LHe Refill and SHe Conversion

The second phase of TPE II, configured as in Figure 10 and summarized in Figure 11, began with a LHe refill of the empty DSS which started at 1100 on January 18 with transfer from a full 500 ℓ SD. The DSS was full (243 ℓ) at 1338. The SD liquid level was measured with a superconducting depth probe before and after this fill operation; 360 liters were transferred out of the SD. The efficiency of transfer was thus 243/360 = 68%.

The DSS was held at 3 psig pressure overnight. The TAO appeared as expected. The following morning at 1/19:0940 conversion to SHe was begun with 222 liters of LHe. The lambda point was reached at 1420 with 140 liters of SHe; conversion efficiency was 63%. Pumping continued overnight. The apparatus was configured to permit a low pressure, divided flow measurement to be made. Since V6 was disabled, as described earlier above, the cryostat flow simulation via the fill line had to be connected prior to starting pumpdown. The valve on the LX' dip tube was kept closed until the divided flow tests began. Because of our concerns over air leakage through plumbing connections which were not designed for use with internal low pressure, we constructed plastic bags around the LX' bayonet couplings and maintained a positive GHe purge pressure within the bags.

E. Dewar Warmup Test

At 01/20:1000 with 126 liters of SHe, T1 = 1.677 K and T2 = 14 K the roughing pump inlet solenoid valve was closed to stop the vent pumping and allow the SHe and shields to warm. Our objectives were to measure a typical rate of unpumped warming as will be encountered during prelaunch vacuum maintenance assembly (VMA) shutdown, and to determine whether it would be feasible to reach steady state shield temperatures more rapidly by forcing the inner VCS to warm rapidly to a near steady state temperature then hold it by resuming the vent flow. The average bath warmup rate over 5 hrs was 35 mK per hour. At that rate the SHe would not have reached T_λ for an additional 9 hrs. We concluded from this that the maximum 4-hour VMA down time restriction which we have levied on KSC for prelaunch operations is conservative and may probably be increased. Final assessment will be made at the conclusion of the TPE series.

F. Dewar Repump Test

To verify that the VMA would be able to reduce the temperature of a somewhat warmed dewar and to prepare for the subsequent test, SV was opened at 01/20:1500 with a Leybold-Heraeus S16 roughing pump on-line instead of the S60 pump used previously. T1 was 1.851 K. The SHe continued to warm slowly for about 1 hr to a maximum temperature T1 = 1.857 K, then began to cool at an average cooling rate of 6.7 mK per hour, reaching 1.739 K at 01/21:1000.

G. Porous Plug Gas Flow Test and Plug Blockage

This important test was to verify that the porous plug could pass an adequate flow of cold helium gas when it was not wet by liquid. When the test was started at 01/21:1000, T1 = 1.743, corresponding to a vapor pressure of 9.97 torr, T5 and T6 on the porous plug had resistances of 40.8 Ω and 66.5 Ω = 16.825 K, respectively, F1 = 6.7 mg/s, and the vent line pressure PV4 was 8.7 torr. The porous plug bypass valve V5 was closed firmly to force all vent flow through the plug. F1 fell immediately to 0.73 mg/s and PV4 dropped to 2.0 torr, as a result of the introduction of the relatively high plug flow impedance into the line. Therefore the pressure drop across the plug was 8.0 torr. T5 and T6 began to cool slowly (resistances increased), and F1 slowly increased reflecting the directly proportional temperature dependence of the plug flow impedance. The plug cooling accelerated as did the flow rate. Between 01/21:1130 and 01/21:1230 T6 cooled from 9.214 to 3.992 K and F1 rose from 1.38 mg/s to 3.98 mg/s. Thereafter the temperatures and flow rate changed very slowly. The test continued overnight with T1 warming continuously; at 01/22:0700 T1 = 1.778, T5 and T6 resistances were 892.1 Ω and 626 Ω = 3.846 K, respectively, F1 = 4.92 mg/s and PV4 = 7.0 torr.

Prior to this time it had been found that readout of the superconducting depth probe (LL) in the automatic periodic "sample" mode was unreliable. Consequently we would occasionally set the probe meter to a "continuous" reading to verify correct measurements. At 0705 on January 22 the LL was read on "continuous" for a few seconds. Within 10 min F1 dropped to 1.20 mg/s and reached 0.28 mg/s by 0747 indicating high flow impedance; T6 rose to 12.8 K. This time the flow did not recover and T5 and T6 began to warm rapidly. Clearly the plug had been physically blocked, probably by contaminants which had been flash evaporated from LL, convected upward directly into the vent line, and pulled into the plug. The SHe also began warming at approximately 1 mK/min which was more rapid than during the deliberate warmup test (Section IV.E). This rapid warming, shown in Figure 11, resulted from higher T2 and less liquid mass than during the earlier warmup. At 0800 V5 was opened but T1 continued rising slowly. At 1050 with T1 = 1.884 K the S60 pump was again turned on and T1 began cooling. The DSS was allowed to repump for 27 hrs.

H. First Divided Flow Test

As stated earlier and shown in Figure 5, LX' had been installed in the DSS fill bayonet FR prior to the SHe conversion to permit a divided flow measurement simulating gas diversion to the cryostat. LX' was connected to roughing pump RP2 and flow meter F2. At 01/23:1515 the manual shutoff valve on LX' was opened permitting flow out of the TA manifold, through V17 and the fill circuit to RP2. The very small bore of the LX' line and withdrawal tube prevented F2 from exceeding 1 mg/s. After 47

hrs we decided to perform the divided flow with the large bore transfer line LX. Since V13 and V6 were inoperat~~ive~~, this changeover had to be done at $P > 1$ atm. The DSS was pressurized to ~ 1 psig with GHe via the vent line termination. The SHe warmed to T_λ quickly, then rose slowly. LX was installed into FR and RP2 + F2 connected to its outboard end. At about 01/25:1500 the divided pumping was resumed with T1 = 2.26K and LL = 90.6 ℓ. Problems with the flowmeters were resolved by the following morning.

The DSS was left undisturbed until 01/28:0800 when the test had to be terminated in order that the dewar could be moved into the flight support structure. During the available time F1 rose from 4.5 mg/s to an approximately steady value of 5.5 mg/s while F2 rose and leveled off at 14.5 mg/s. Over this period T2 rose slowly due to the reduced F1 and was approaching a steady value of about 34 K. T1 held at a steady value of approximately 1.8 K.

I. End of Test

At 01/28:0800 the DSS was pressurized so that it could be removed from the fixed table and installed in the FSS which had previously been assembled onto the Transportation Support Structure or dummy pallet. This activity took several hours during which the dewar, containing 60 liters of warming LHe, was lifted a number of times by a pair of eye bolts on the TA top dome-to-case flange. From January 28 to February 3 the 4.28 K LHe evaporated at an average rate of about 0.46 liters per hour. During the last 48 hrs the rate had decreased to 0.40 liters per hour which is somewhat greater than the 0.35 liter per hour evaporation observed in TPE I.

After the last LHe evaporated at 02/03:1300 the shields warmed slowly by themselves. T2 rose from 28 to 190 K in 138 hrs.

J. TPE II Conclusions

We have drawn the following conclusions from TPE II:

1. The modifications made after TPE I to prevent air ingestion were successful, though some were temporary.

2. The DSS can be operated with a large quantity of SHe in the upright attitude.

3. An already cold dewar can be refilled more efficiently than can a warm dewar, and stabilization time is reduced, as one would expect.

4. The DSS steady state performance with SHe is satisfactory. Steady state boiloff was 8.0 mg/s or 4.75 liters/day corresponding to a total heat load of 186 mW. Storage efficiency was 1.9% per day. If the flight dewar were in a stand-alone mode, 125 liters of SHe would last 26.3 days.

5. The DSS operates satisfactorily and stably in a divided flow mode in which a portion of the evaporated helium gas is diverted from the cooling of the dewar VCS and delivered directly to a separate thermal load simulating the cryostat VCS. In the particular flow division ratio achieved in this TPE, the dewar VCS flow stabilized at 5.5 mg/s and the simulated cryostat VCS flow at 14.5 mg/s for a total vent flow rate of 20.0 mg/s or 11.9 liters/day (SHe). At this rate 125 liters could last 10.5 days. The net heat load on the SHe was 464 mW.

V. TPE III

This TPE did not accomplish any of its intended objectives except to reverify LHe filling operations and system safety (see Table 3). The new objectives for TPE III were 9, 12, and 15. This was the first operation with the apparatus installed in the FSS which, in turn, was mounted in the RSS, as shown in Figures 12 and 13. Activities are summarized in Table 6. Figure 14 is a schematic of the system configuration.

On February 11, 1982, the DSS was cooled and filled with 182 liters of LHe. In preparation for the first divided flow test (see TPE IV) the laboratory transfer line LX' was left connected to the fill bayonet FR with a relief valve on the outboard end. A second relief valve was installed on the vent line as usual. Inadvertently the valve on the vent had a higher cracking pressure (4 psig) than the valve on the fill line ($\sim$ 1 psig). As a result, the system relieved through the fill circuit. Because the internal fill tube extends to the bottom of the dewar, liquid was forced back through the fill line. By the following morning there was no liquid left in the dewar. We first suspected serious thermal or vacuum problems in the DSS, and began to warm the system rapidly. After a short time we were relieved to discover the correct explanation, and stopped the active warmup. New liquid helium was ordered for TPE IV.

VI. TPE IV

This TPE was started at 0820 on February 22, 1982, with the system in the same configuration as in the abortive TPE III (Figure 14). New objectives were those of TPE III, namely 9, 12, and 15. Objectives accomplished are shown in Table 3. Table 7 is the index of major events during the 16-day operation, and Figure 15 is a graphical summary.

A. Fill and Conversion

Cooldown and transfer from a nearly full 500 liter SD began at 0820 on February 22, 1982, and proceeded smoothly. The DSS was full (250 ℓ) at 1200, 375 ℓ being removed from the SD. Transfer efficiency was 67%. Within 30 min the apparatus was ready for conversion to superfluid. Bayonet connections being used in nonstandard ways (e.g., LX' in the FR) were bagged and purged with GHe to prevent possible air ingestion. Pumpdown began at 1236 with 232 ℓ in the vessel. The lambda point was reached at about 1800 with 123 ℓ remaining. Conversion efficiency was 53%. Pumping continued overnight.

B. Divided Flow Test

By 0730 on February 23 T1 had reached 1.792 K with 101 ℓ remaining in the dewar. The divided flow-test was started and continued for 6 days. Figure 15 shows F1, the mass flow rate through the standard dewar heat exchanger vent, F2, the diverted mass flow rate being drawn from the TA manifold directly out through the fill circuit, F_{TOTAL}, and the total mass flow rate.

The goal was to set F2 close to 10 mg/s, adjust F1 as necessary to maintain reasonable liquid helium temperatures, and observe the response of the system. First F2 was set to 10 mg/s by valve MV2 (see Figure 14). F1 was about 15 mg/s. After 25 hrs F1 and F2 were again adjusted (C' in Figure 14); 7 hrs later F2 was adjusted; 49 hrs later F1 was decreased to 5 mg/s; then 25 hrs later F2 was again set to 10 mg/s. Throughout these manipulations F_{TOTAL} stayed in or recovered rapidly to the range 22 to 24 mg/s and T1 stayed in the range 1.80 to 1.94 K. T2, the inner VCS temperature, moved inversely as F1 as one would expect and stayed in the range 32 to 37 K. Throughout this divided flow period the rate of decrease of LL corresponded to an evaporation rate of 20.1 mg/s, in excellent agreement with F_{TOTAL}.

C. SHe Stabilization

For the next 3 1/2 days following the divided flow measurements, the dewar was allowed to restabilize with flow through the dewar vent only. For 24 hrs full flow was set and T1 cooled from 1.95 to 1.81 K. At 0925 on March 2, when F1 had fallen to only 18.0 mg/s, MV1 was closed partially to reduce F1 to 8.5 mg/s; further adjustments were made to hold that flow. Over the next 3 1/2 hrs T1 rose to 2.1 K, a much more rapid heating rate than experienced earlier. At 1200 on March 2 F1 was fully opened to recool the system.

Comparison of the heat load into the SHe in this TPE, as evidenced by the 20 mg/s boiloff and slower cooldown with the approximately 8 mg/s rate observed in TPE II, leads us to conclude

that there was probably a somewhat soft vacuum in either the dewar guard volume or the TA interior. That is, there probably existed a minute leak in the helium container or the TA plumbing which permitted gaseous helium to enter one or both of the vacuum spaces and cause an increased heat transfer into the liquid helium. The contaminant was almost certainly not air, unless the leaks were very large, since air constituents would be cryopumped directly onto the cold surfaces, the heat load then being primarily heat of condensation. Since we had no vacuum gauge sensing the TA or dewar vacuum spaces during this TPE, we only had the indirect evidence of the increased heat load. (Leak tests conducted between TPE's V and VI identified the leaks which were repaired.) At the time, however, the existence of the high heat load was masked by the divided flow manipulations: we attributed the high total flow only to the reduction of F1.

Because of this heat load problem we can only draw qualitative conclusions regarding the relative behavior of F1 and F2. These conclusions will be covered in conjunction with the discussion of TPE VI divided flow (Section IX.D).

D. Porous Plug Gas Flow Test

At the end of the stabilization and recooling operations just discussed, a second porous plug gas flow test was attempted. V5 was closed lightly at 1047 on March 3. Gas flow dropped to $\sim$7 mg/s and T5 and T6 did not cool. It was soon apparent that V5 and V17 might not be fully closed. The valves were carefully closed even further several times. Eventually a flow rate of $\sim$2.5 mg/s was reached, and we concluded that the majority of the flow was passing through the plug. The plug cooled only slightly, the flow rate rose only slightly and the helium bath warmed toward T_λ fairly rapid, further verifying the existence of an anomalously high heat load. This plug flow test was inconclusive.

E. Manual Valve Closure

During the preceeding plug flow test it became clear that we did not have an adequate understanding of the operation of the three manual cold valves, V5, V7, and V17, particularly the torques required to close the valves without over-deforming their copper stem inserts. Consequently several measurements were made during and after the present TPE to develop a valve closure procedure and specification. This work is discussed in Appendix B. It was concluded that a closure torque of 9.0 inch-pounds would give a safe, reliable, superfluid-tight closure.

F. End of Test

As in TPE's I and II, the final LL reading was LL = 6.6 liters, the lower limit of LL readout. This occurred at 11:40 on March 3. At about 14:00 on March 4 the last helium evaporated and the shields began to warm. Boiloff of the final

6.6 liters in 26 hrs corresponds to a mass flow rate of 10 mg/s, which is half the rate of the preceeding portion of the TPE, although it should be noted that following the completion of the divided flow test, the dewar flow rate continuously increased. Shield warmup was much more rapid than previously seen.

G. TPE IV Conclusions

At the end of TPE IV the following new conclusion could be drawn. From a qualitative viewpoint divided flow leads to the general behavior we expected. That is, diverting some cold gas through a simulated cryostat circuit reduced the net cooling of the DSS shields which then warmed somewhat. The warmer inner VCS increased the total heat load on the bath which warmed slightly; the increased vapor pressure then caused both F1 and F2 to rise. Because of the large thermal mass of the bath and the nonlinear vapor pressure characteristic of SHe, several valve adjustments may be required to achieve a particular steady-divided flow condition and, further, only one of the two flows can be independently controlled.

VII. TPE V

This TPE was started as soon as an LHe supply was available after TPE IV. The main objective was to verify the tight closure of the cold manual valves and then to tilt the system and determine whether the porous plug would operate correctly with SHe. Specifically the intended objectives were 9, 11, 15, 16, 17, and 18. We were concerned at the outset that the high heat load referred to in the TPE IV discussion might prevent the plug from operating at all as a fluid restraint. This problem did not in fact occur; objective 9 was fully satisfied and useful data on the remaining objectives were also obtained as shown in Table 3. Figure 16 shows the schematic system configuration, during the tilt tests.

Table 8 is the index of major events during the 13-day operation and Figure 17 is a graphical summary of the complete TPE: Events E, F, G, H, and I are the separate tilt tests shown graphically in Figures 20, 25, 26, and 32, respectively. It should be remembered that T5 and T6 on the porous plug were both in nonstandard configurations, T5 was in a three-wire arrangement, and T6 in a two-wire arrangement. Consequently their calibrations could not be trusted during the conduct of the TPE. Since their resistances varied inversely with temperature, trends in porous plug temperature could be observed. (See Section VII.C for discussion of in situ correlation and calibration of T5 and T6.)

A. Fill, Topoff, and Conversion

Chilldown and fill of the DSS with LHe was started from a nearly full 500 ℓ SD at 1300 on March 9, 1982, with T2, T3, and T4 at 213, 236, and 256 K, respectively. The DSS was upright and mounted in the RSS. Liquid collection began at about 1430 and

was complete at 243 ℓ at 1555. Liquid volume removed from the SD was not recorded. The system was left to vent through a relief valve overnight. The next morning at 0700 with 200 liters in the DSS, a topoff was conducted for the first time. Less than 4 liters were lost from the dewar as the fill and lines were chilled via the V17 bypass valve and the transfer was then directed back into the dewar. The dewar was again filled to 243 ℓ.

Slow conversion to SHe was immediately started at 0815, the lambda point was reached at 1230, and the system was allowed to operate undisturbed for 24 hrs. During this latter period 14.5 liters of SHe boiled away and at the end of this stabilizing time the flow rate was 12.5 mg/s, indicating again the high heat leak the dewar was experiencing.

B. Porous Plug Gas Flow Test

At 1240 on March 11 V17 and then V5 were closed to 9 inch-pounds torque. The flow rate dropped to about 0.7 mg/s and both T5 and T6 on the porous plug began to warm (resistance increased), as did the bath and heat shields. The test continued for 1 hr at the end of which T6 had warmed from 16 to about 20 K, and the bath had warmed from 1.72 to 1.78 K. Twenty minutes before the end of the test V7 was torqued closed to 9 inch-pounds to determine whether it would have any effect on the warming trend. No effect was apparent. V7 was then reopened as a safety measure for overnight repumping of the system.

Although this dedicated plug cold gas flow test was not successful (due certainly to the high gas conduction heat load onto the plug module which prevented the plug from cooling adequately), later observations of gas flow during tilted operations verified the gas flow capabilities of the porous plug.

C. First Tilt Test

The initial tilt test was done very slowly and with a number of precautions which were unnecessary in later tilting. Since we had not previously flowed superfluid helium into the assembled TA, tilting was done in small angular increments in case a large helium leak was detected (none was seen). Because V7 provides a direct path from the cold TA to the warm fill plumbing, it must remain tightly closed during tilting when it may be immersed in SHe. Consequently when this tilt test started, V7 was closed to a 9 inch-pound torque, the external fill lines were evacuated and leak checked, and a barocel vacuum gauge was connected to the circuit and monitored for evidence of helium leakage past the seat of V7 (none was observed). V7 leakage monitoring connection can be seen on the fill receptacle in Figure 18. V5 and V17 were also closed to a 9 inch-pound torque.

Figure 19 is a scale drawing of the liquid vessel and the dewar/TA plumbing showing in particular the relationship of the vent line, trap, porous plug, and gas manifold. In the tilt test discussion below angular position rotation is as follows: it is measured with respect to the vertical and $\theta = 0°$ corresponds to DSS upright; positive angles are toward the launch attitude (cryostat above DSS, Figure 18) and $\theta = 90°$ is the launch angle; negative angles give an inverted attitude and more fully simulate low gravity space conditions ($\theta = -120°$ is shown in Figure 22). θ is also defined in Figure 19.

Figure 20 is a graphical summary of the first tilt test on March 12, 1982, which is event E on Table 8 and Figure 17. Figures 21 and 22 show on an expanded time scale period (from 1600 to 2010) which includes the first immersion of the porous plug in superfluid helium. Figures 23 and 24 likewise show the second and third immersion periods. Since there is a great deal of useful information shown in these figures, we will discuss them in detail. Figures 20 through 24 show the following data: temperatures T1 (bath), T2 (inner vapor cooled shield), T5 (liquid side of porous plug), and T6 (downstream side of porous plug); flow rate F1 (mg/s); tilt angle θ (degrees); measured or estimated liquid volume (liters); status of V5 (plug bypass valve) and MV1 (vent line vacuum pump inlet valve); wet or dry status of plug; and hydrostatic head of SHe (centimeters), estimated graphically on Figure 19 and indicated by numbers in parentheses along the angle status curve. In these and subsequent figures the T6 data are shown as corrected by matching T6 and T5 at 1642 hrs on March 12 when the plug was clearly wet. T5 in turn was calibrated by matching the manufacturer's response curve to T1 at 1700 hrs. The choice of these calibration times is discussed later. Corrected values of T5 and T6 are shown in Figures 21 through 23.

1. First Plug Wetting

When tilting began the dewar contained 130ℓ of SHe at T1 = 1.77 K. V5 was closed and F1 through the plug fell to about 0.7 mg/s, as in previous plug gas flow tests when the plug was relatively warm. The bath T1, T5, and T6 began to warm slowly.

Tilting was then done slowly and incrementally. When $\theta = 87°$, fluid should have started flowing into the vent line, according to Figure 20. When $\theta = 90°$, the rate of bath warming abruptly increased from 0.96 mK/min to about 2.4 mK/min, indicating that heat from the warmer TA plumbing was beginning to flow along a liquid/gas column into the bath. At the same time F1 began to increase more rapidly and soon thereafter T5 and T6 began to cool. At $\theta = 93.5°$, fluid should have been able to flow over the plumbing trap. The fact that it did not do so for more than 40 min, and after θ had been increased to 98° (hydrostatic head = 18.5 cm or 2.0 torr), indicates that a vapor lock existed in the plumging until about 1625 hrs.

When T5 and T6 began to register liquid at the plug, F1 jumped to about 45 mg/s and the rate of warming of the bath decreased. T5 and T6 behaved erratically for about 10 minutes, then became smooth except for a small jump at 1640. Beginning at 1646 θ was gradually returned to 90°. At about the time θ reached 90° and with F1 = 46 mg/s, T2 became constant at 2.032 K.

During the initial high flow period T2 rapidly fell from 25 to <10 K and remained there for a long period. We initially interpreted the fall of T2 as being due to liquid passing through the porous plug and reaching the heat exchanger on the inner vapor cooled shield (see Figure 19). However the same fall in T2 to <10 K occurred in earlier TPE's (Figures 4 and 9) when F1 was high but the DSS was upright and no liquid could have been in the TA. Consequently we have concluded that the present data show that bulk SHe was properly restrained by the original porous plug at a hydrostatic head of up to 18.5 cm or 1.97 torr with full pumping. Further evidence of the liquid on the plug is the following:

The system was held at θ = 90° from 1714 to 1943, a total of 249 min, during which time T1, T2, T5, T6, and F1 stabilized and then decreased very slowly. For example T1 = -0.16 mK/min. Since the average liquid volume in the dewar was 129 ℓ, it is certain that the vent tube between the dewar vessel and the trap riser in the TA was completely filled with SHe. The liquid rose $\sim$1 cm up into the trap riser, and the liquid equilibrium level lay 1.1 cm below the liquid (T5) side of the plug.

At 1943 the system was tilted to θ = 85° and held there for 40 min. This raised the TA plumbing and caused all of the liquid in the vent line and trap riser to flow back into the dewar. Any liquid on the plug side of the trap was kept there by the trap and the system liquid equilibrium level now lay 10.7 cm below the top surface of the 0.64 cm thick plug. At this time T5 and T6 increased abruptly by 8 mK and then remained approximately constant. T1 was not affected by this tilting and continued to decrease slowly. Fourteen minutes after the tilt, T5 suddenly warmed, indicating that the upper surface of the plug had gone dry. Six minutes thereafter the downstream side of the plug also began to go dry, and at 2006 the final SHe evaporated from T6.

It seems clear from the above evidence that the porous plug was: (a) wet by SHe during the period discussed, and (b) holding SHe and permitting only GHe to leave. The question "by what means did the plug stay wet?" remains; since, after θ was reduced from 98° to 90°, there was no path between the bath and the plug by which liquid could flow by any classical mechanism.

The plug remained wet by two means: (a) liquid mass remaining in the plug module above the plug and in the tube connecting the trap to the module after the system was tilted back to 90° and (b) mass transported over the trap. We estimate that the total internal volume above the plug is about 65 cm^3. At F1 = 45 mg/s = 18.6 cm^3/min this volume of liquid would be depleted in 3.5 min. Consequently mass must have been transported from the dewar over the trap to the plug.

Two transport mechanisms seem possible: first, superfluid film creep-up over the trap and down to the plug and, second, evaporation on the dewar side of the trap, gas flow over the trap, and recondensation above the plug.

To estimate the film creep mechanism we note the general rule that "the creep rate (on a clean surface) is 1 cm^3 gas (NTP)/min (say about 1 mm^3 liquid/min) for every millimeter diameter." Since the trap riser tube is about 1/2 inch o.d. its maximum creep rate is 12.7 mm^3/min or 0.013 cm^3/min. Clearly film creep is 3 orders of magnitude smaller than F1 and can be ignored. This leaves evaporation in the dewar with recondensation at the plug as the only reasonable means of mass transport. Such a mechanism in turn requires that T5 be somewhat colder than T1.

With θ = 90° and the vent line full of SHe at T1, evaporation takes place at the bottom of the 1/2 inch diameter trap riser and the approximately saturated vapor flows about 20 cm to the plug module where it recondenses at T5. Prior to 1943 hrs T5 was approximately 80 mK colder than T1. Maximum flow rate over this path was at least 45 mg/s, since the plug did not go dry. When θ was raised to 85°, SHe poured back into the dewar and the transport path increased by the length of the vent line to about 102 cm. If the volume of SHe above the plug at that time was as much as 65 cm^3 as discussed above, it would have contributed no more than 65 cm^3/14 min = 4.6 cm^3/min to the observed 18.6 cm^3/min flow. Alternatively we can argue that the 65 cm^3 would have lasted only 3.5 min at 45 mg/s, and thus mass resupply must have been taking place. Consequently vapor transport from the dewar vessel to the plug module continued and was about 14 cm^3/min over the 102 cm path. That this mass flow continued when T5 was indicated to be 3-4 mK warmer than the bath suggests that the T5 (and thus the T6) curves should be corrected downward by perhaps 5-10 mK to provide the necessary thermal driving force.

2. Second Plug Wetting

Additional evidence of the system/porous plug processes can be seen in the remainder of the first tilt test. From 2006 to 2047 the plug was dry, but T5 and T6 never exceeded 2.90 and 2.75 K, respectively. F1 remained greater than 35 mg/s and T2 did not warm. More significantly T1 continued to cool,

demonstrating conclusively that dewar cooling by gas conduction through the original porous plug would be quite satisfactory provided the plug stays relatively cold.

At 2021 the system was tilted from 85° to 90° with full vent pumping. Twenty-one minutes later the plug was again covered by SHe and F1 rose to 45 mg/s (Figure 23). Vapor transport is the only significant source of the SHe. As in the first plug wetting T5 and T6 were somewhat erratic initially, drifting by as much as 10 mK in several minutes. However T6 always remained cooler than T5.

At 2104 MV1 was throttled slightly as indicated by the downward pointing arrow on the lower edge of Figure 23; T5 and T6 immediately warmed by 5 mK and stabilized. MV1 was further closed at 2108, 2115, and 2120. Following each of these three times T5 and T6 warmed further suggesting that the available evaporative cooling was not quite sufficient in the presence of the high TA gas load. At 2124 when MV1 was closed further, T6 suddenly warmed by 85 mK to about 2.075 K and stayed essentially constant while T5 remained at the bath temperature and decreased at the same rate as T1. It appears certain that until 2124 SHe penetrated completely through the plug, and evaporation at the downstream surface kept T6 cooler by 3-4 mK, after 2124 the liquid/gas interface receded back into the plug and the evaporating gas warmed slightly as it flowed out to the T6 sensor. At 2142 MV1 was again closed further, the vent flow no longer provided sufficient cooling at the plug, and the plug dried out completely. As it warmed, F1 decreased and T1 stopped cooling.

Just before 2200 MV1 was opened slightly and θ was increased to 91°. With an estimated 126 liters of SHe this tilt was not enough to cover the trap. F1 increased smoothly then became constant at 30 mg/s.

3. Third Plug Wetting

In Figure 24 we see the third plug wetting sequence of the first tilt test. It was performed with a moderate to high hydrostatic head whereas the first two wetting sequences involved small hydrostatic heads with full pumping and restricted pumping, respectively. As we will discuss, the system responded quite differently.

At 2219 θ was increased to 95° and the SHe rose over the trap, giving a hydrostatic head on the plug of about 10.7 cm or 1.1 torr. F1 immediately rose to 42 mg/s and the plug became wet on both sides. ΔT across the plug was only about 1 mK. From 2226 to 2238 MV1 was gradually throttled. In the previous sequence with no hydrostatic head when F1 was reduced to about 38 mg/s, the downstream side of the plug went dry and warmed, but the upstream side remained wet. In the present case F1 was reduced to about 7 mg/s before any warming was seen. At that point the system went into a new mode of operation.

At 2238 with θ = 95° and F1 = 7 mg/s, T1 began to warm at 9.6 mK/min, and T5 and T6 at 2 mK/min. At 2247 there was an inexplicable 15 mK decrease in T5 and T6. Subsequently T5 warmed 2.4 times faster than just previously and T6 warmed 4.6 times more slowly. It is clear from this that even though there should have been a continuous SHe column from the bath to the porous plug, so that T1 $\simeq$ T5 (as existed prior to 2238), a vapor bubble must have formed between the plug and the bath, probably at the trap. The plug warmed well above the bath temperature due to the high TA heat load and heat was apparently transported via the vent line into the bath which warmed. At 2252 MV1 was fully closed. There was a slight drop in T5 which then continued to warm rapidly. T6 soon began to warm faster as well. Finally T5, then T6, went dry.

At 2316 θ was increased to 100°; the hydrostatic head was 23.0 cm or 2.4 torr and at 2317 MV1 was opened. The plug again became fully wet at 2318, and F1 rose to 46 mg/s. Now with full pumping and a 2.4 torr heat, T5 and T6 oscillated by about 15-20 mK with a period of a few minutes and F1 also appeared to oscillate. T6 remained a few mK cooler than T5. The flow and temperature oscillations increased, so MV1 was throttled somewhat at 2331 reducing the amplitudes of the oscillations. At 2341 θ was reduced to 90° and the oscillations immediately disappeared. It is not clear whether this was due to the reduction of the pressure head or to the severing of the liquid path from the plug to the bath, but the head reduction is probably the explanation.

When the oscillations stopped, the bath stopped warming and became constant. About 30 min after the tilt to 90° the plug dried out in exactly the same manner as it had the first time at 2000 hrs. V5 was then opened and the system was left at 90° overnight. It gradually cooled to a bath temperature of 1.786 K at F1 = 18.65 mg/s.

D. Second and Third Tilt Tests

The second and third system tilt tests, events F and G, were done in short periods of time on March 13 and 14, respectively. Since the volume of SHe remaining at the time of the two tests had fallen below the vent line entrance, a greater tilt angle was needed to pour liquid into the TA. On March 13 a head of about 1 torr was used with full pumping, while on March 14 a head of 3 torr was maintained as MV1 was throttled. As seen in Figure 25 the bath warmed during both tests when the plug was wet.

On March 13 with full pumping the plug dried out twice, each time after θ was reduced below 95°, and it rewet when θ was increased to 96° or more. The angle at which fluid could flow over the trap at a liquid volume of 113 ℓ was estimated from Figure 19 to be 95.5°. At the end of the test after the system was tilted from 99° to 90° the plug dried out in 8 min.

On March 14 θ was held at 105° while the plug was wet. With an estimated 103 liters the angle for flow over the trap was 96.5°. Initially some oscillations were observed. MV1 was throttled several times, the oscillations stopped, and the plug went from T6 < T5 to T5 < T6. After MV1 was closed fully T5 went dry in 6 min, stayed dry for 6 more minutes until MV1 was reopened and immediately became wet again; T6 stayed wet continuously. When θ was raised to 90° the plug dried out in 3 min.

E. Fourth Tilt Test

The fourth tilt test, event H, took place on March 15 and involved six separate periods during which the porous plug was wet by SHe, the last two with the system tilted into the inverted attitude. A summary of these results is shown in Figure 26. At the start the liquid volume was only 87.4 liters as verified with LL by rotating the system upright and waiting a few minutes for sloshing to die down. At this volume a tilt angle of about 99° was required to pour liquid into the vent line after which it could easily flow over the trap; hydrostatic head was then 13.2 cm or 1.4 torr.

Details of plug operation are discussed below for four of the six wet periods, because each has some features not seen in the plug sequences previously described (Sections VII.C and VII.D).

Figure 27 shows the wet period following 0830 on March 15. With a large hydrostatic head (3.6 torr) at θ = 110° and a flow rate of about 35 mg/s, there was only a 1-2 mK temperature gradient across the plug (T6 < T5) which was about 50 mK warmer than T1. T1 was warming at a rate of about 1.3 mK/min. Note that the T1 sensor was 19 cm above the liquid level. At 0853 θ was reduced to 100° and T5 and T6 immediately fell 30 mK, with T5 < T6. When θ was reduced further to 95°, breaking the liquid column from bath to plug, T5 and T6 did not immediately respond. After 5 min T5 began warming at a rate of 8.6 mK/min. By the time T5 exceeded T_λ at 0922, T5-T6 was 278 mK. T6 went dry at 0925. From the time T5 began warming rapidly until T6 went dry, about 320 cm^3 of liquid passed through the plug. Therefore a significant volume of SHe seems to have participated in the warming evidenced by T5.

The next wet plug period, commencing after 1110 on March 15, is seen in Figure 28. When the plug became wet, θ was 110° and F1 rose to about 50 mg/s. For about 12 min T5 and T6 were well behaved and T5-T6 = ΔT = 13 mK. Then vent line pressure (not shown) and plug temperature oscillations started, accompanied by two brief peaks in F1. At 1134 MV1 was fully closed. T1 began warming more rapidly as F1 fell to zero. The oscillations persisted, their amplitude increased somewhat, and the plug ΔT increased to about 20 mK. In spite of the unsteady behavior T5 and T6 remained well below T_λ and no "catastrophic" effects were apparent. At 1205 T5 went dry and 10 min later T6 went dry.

At 1355 with 83.4 liters in the dewar the system was tilted into the inverted attitude ($\theta < 0$). Figure 29 is a photograph of the DSS at this time, and Figure 30 shows this period graphically. The only physical difference in the system is that the trap no longer presents a barrier to flow to the plug and T6 is situated above T5, as seen in Figure 19. With 83 liters an angle θ of at least -102° was required to bring the liquid level to the vent line entrance. Figure 26 shows that T1 was cooling from 1330 to 1400 but that it rapidly warmed when the system was rotated to -90°. To confirm that this resulted from quickly removing the T1 sensor from the liquid, θ was returned to -38° at 1408, rewetting T1 which immediately dropped from 2.29 to 2.11 K. Clearly the bath continued cooling as the following tilt test proceeded, even though T1 read much higher temperatures.

Soon after θ was increased to -110° the plug became wet, T5 starting out at about 2.14 K which was 30 mK warmer than the probable bath temperatuare. At this time T1 actually read about 2.4 K; the T1 sensor was 20 cm above the liquid surface. The hydrostatic head was 33.5 cm or 3.6 torr and the plug temperature oscillated slowly as observed in earlier situations with high hydrostatic head. T5-T6 was about 27 mK throughout the unstable period.

At 1431 θ was reduced to -105° and later to -104° at which angle the hydrostatic head was 21 cm or 2.2 torr. The oscillations disappeared and T5 and T6 began cooling. T5-T6 dropped to 24 mK and then slowly decreased to 19 mK over the next hour. Throughout this period F1 was very high, probably more than 50 mg/s. The T1 sensor, though still 17 cm above the bath surface, slowly cooled until when the plug dried out T1 and T5 were essentially equal.

At 1540 the plug temperature inexplicably rose by 10-20 mK and T5-T6 increased to about 30 mK. At 1602 T6 went dry and 4 min later T5 also went dry.

Figure 31 is a continuation of Figure 30 and shows the rapid rewetting of the plug when the system was tilted further by 1° at 1605. Shortly after θ was returned to -90° T5 warmed rapidly reaching a maximum of 2.45 K at 1638, then cooled through a minimum of 2.10 K, then slowly rewarmed. Clearly evaporation was occurring within the plug and the vapor then warmed before contacting the T6 sensor. Meanwhile T5 continued to cool, remaining about 10 mK warmer than T1. T5 finally went dry at 1754, 88 min after the tilt to 90°. Total helium transported through the plug during this time was 264 g or 1.82 liters of SHe.

F. Fifth Tilt Test

During this test, event I, we attempted to keep the system in an essentially steady state condition for a long period of time. As seen in Figure 32 this test started with 66 liters remaining in the dewar. The tilt angle to pour liquid into the vent line was -109°. The plug was wet and θ adjusted empirically

to 110° at which angle temperatures became well behaved. The hydrostatic head is shown on the θ curve for each angle in the following sequence.

The system was left undisturbed for, 4 hr until the plug temperatures indicated incipient drying out. During this time F1 and the temperatures rose smoothly to a maximum and then decreased. At 1309 T1 = 1.989 K, T5 = 2.001 K, T6 = 1.983 K, and all were decreasing slowly; F1 was decreasing rapidly, heralding the dryout of the plug. T6 then began rising rapidly and θ was increased by 1° to -111°. Immediately T6 recooled and over the next 2 hr, 20 min, the system repeated the previous slow rise and fall. At 1520 T5-T6 = 11 mK. T6 then rose within a few minutes as F1 began falling more rapidly, and T5-T6 remained at $\sim$ 3 mK. At 1537 θ was again increased by 1° and a third repetition of the system behavior occurred.

G. Plug Heater Test

A 6 kΩ wire wound resistor is pressed lightly against the downstream side of the porous plug, next to the T6 sensor. We expected, with the plug wet by SHe throughout and with the expected plug temperature profile with T6 colder than T5, that applying heat on the downstream side would decrease or reverse the temperature gradient and permit an increased mass flow through the plug. This greater flow would facilitate cooling of the cryostat during the Spacelab 2 flight. In this test the heater H3 was energized to measure this flow control mode. We realized that with the already high heat load on the plumbing due to the helium gas in the TA guard the heater function might not be readily observable.

A small current was passed through H3 in five steps. Table 9 shows the key system parameters before, during, and after these steps and the system responses. It is clear that the heater has very little effect on plug temperatures and system flow rate, even when a rather large power is dissipated. The heat-induced flow increase was observed, though it was much less than anticipated.

H. End of Test

Immediately after the heater test the system was rotated to the vertical and was allowed to come to steady state with full pumping (V5 open). Prior to rotation to vertical θ = 112° and with 57.9 liters in the dewar the T1 sensor was located about 26 cm above the SHe surface. When T1 was immersed in the SHe, there was no change in its reading, confirming first, that film flow was keeping T1 at the bath temperature over a vertical height of 26 cm, and second, that the high heat load into the system was probably confined to the TA guard volume alone. If the dewar guard were also soft, conducted heat into the structure of the inner vessel would probably have caused T1 to run much warmer than the true bath temperature.

As seen in Figure 17, the system was approaching steady state when the liquid was exhausted on March 21. Steady state conditions (at 03:21:0000) were T1 = 1.912 K, T2 = 41.7 K, T3 = 83.8 K, T4 = 147.6 K, and F1 = 25.4 mg/s. The average boiloff rate from March 10-21 was 0.56 liter/hr or 22.5 mg/s.

After the last liquid evaporated an active GHe purge was started so that leak checks and hardware modifications could be started.

I. TPE V Conclusions

We have drawn the following new conclusions from TPE V:

1. The TA plumbing was tight from the standpoint of gross helium leaks. Rotation of the system to angles as great as 112° from vertical in either direction was possible without a serious loss of guard vacuum.

2. In spite of the preceeding conclusion one or more small leaks existed in the plumbing (and may have existed since TPE IV). A noncondensible (i.e., helium) gas pressure must have developed in the TA guard volume, resulting in a rather high conducted heat load on the cold TA plumbing. This was observed most dramatically in the heating rates of the porous plug module. When the system was rotated and SHe poured into the plumbing upstream of the porous plug, the leak rate may have increased, but this is not certain. Clearly the leaks must be sealed and it may be necessary to install a passive cryopump in the TA to reduce the impact of leaks which may develop later.

3. When the dewar is tilted to positive angles (toward the 90° launch attitude) in the laboratory, bulk fluid flow to "start-up" the porous plug is inhibited in three ways:

a. Liquid must enter the vent line at the top of the dewar vessel "vertical" centerline in order to flow into the TA. This may require tilting initially to an angle greater than 90° (Figure 19).

b. Liquid must rise high enough in the TA plumbing to flow over the top of the trap in order to reach the porous plug which is approximately on the "vertical" centerline. This may require that the tilt angle be maintained greater than 90° (Figure 19).

c. Liquid must overcome a vapor lock condition which exists in the TA plumbing when rotation first occurs, due apparently to the heat stored in the plumbing materials by virtue of their initial higher temperature. With the dewar tilted over, gravity assists in driving fluid into the TA. Even so, as much as 2 hrs were required after tilting before the plug became wet when V5 was closed (as it will be during the flight) (Figure 20), and from 10 to 30 min elapsed after tilting when V5 was kept open

(Figures 26 and 32). In space the first two factors will be absent, but the third could exist if the plumbing ever warms significantly, as might happen, for example, during the launch phase when venting is stopped. Furthermore the assistance of gravity in collapsing the vapor lock will be absent in space.

4. When the dewar is tilted to negative angles in the laboratory, the plumbing trap does not inhibit bulk liquid flow for plug startup and only factors 3.a and 3.c must be considered (Figure 19).

5. The porous plug which was in the TA at the time of these tests appears in retrospect to have worked successfully as a liquid-vapor phase separator in all cases, in spite of the high heat load on the system (estimated to be more than 1 W) and the high flow rates (30-50 mg/s) which resulted. The decrease of T2 to about 5 K during wet plug operations was probably due to the high flow rate and not to liquid penetration of the plug and flow into the plumbing manifold and inner VCS. The same effect was seen in vertical tests (Figures 4 and 9).

6. There were three mechanisms of helium mass transport from the liquid bath to the porous plug:

a. A fluid column connected the plug to the bath when the tilt angle permitted and the plumbing was cold enough. Arbitrarily large mass flows, much larger than the observed maximum of ~ 60 mg/s, should then have been possible.

b. Superfluid film flow operated at all times, if tubing temperatures were no warmer than T_λ. However maximum film flow rates are 3 orders of magnitude too small to account for observed flows. This mechanism can be neglected.

c. Vapor transport from the bath to the plug by evaporation, flow, and recondensation served to keep the plug wet and the bath cool in many cases in which the liquid column (6.a above) was interrupted. In Figures 21-22, for example, the liquid level was lower than the trap height, but the system operated in steady state for 2 1/2 hrs at 45 mg/s. The condition for vapor transport was that T5 < T1; the greater this difference, the greater the possible mass flow rate.

7. In most cases when the plug was wet by SHe full vent flow was occurring and the system was in approximately steady state. T6 was colder than T5, indicating that the plug pores were completely full of fluid and that evaporative cooling on the downstream side of the plug was generating a fountain pressure in the proper direction to restrain fluid flow. Temperature gradients ranged from 1-2 mK (Figures 21, 22, 23, and 27) to as much as 20 mK (Figures 30 and 31).

8. Steady state operation was possible with full pumping only when the hydrostatic pressure head was of the order of 2.0 torr (18.5 cm column of SHe) or less. (Figures 21, 24, 27, 28, and 30).

9. In some cases in which the plug was wet, full or nearly full pumping was taking place, and the system was approximately in steady state, T6 was warmer than T5 but remained relatively cold (often $<T_\lambda$) (Figures 23 and 31). In these cases we conclude that the liquid-vapor interface had receded into the plug and that the vapor warmed somewhat before reaching the T6 sensor.

10. In several cases of positive tilt (T5 higher than T6) when the plug was about to go dry, T5 would become considerably warmer than T6 (but remain less than T_λ) for several minutes or tens of minutes (Figures 22, 24, and 27). Once T5 went completely dry, T6 would dry out within 5 min.

11. In cases of negative tilt (T6 higher than T5) the dryout sequences of T5 and T6 were essentially reversed (Figures 30 and 31) from the positive tilt situations.

12. The porous plug heater appeared to produce the desired increase in vent flow, at least qualitatively. However the high heat load on the TA masked quantitative measurements of operation of the heater.

VIII. System Modifications

As a result of several factors, a number of changes and repairs to the IRT hardware were made after TPE V was completed. These changes and repairs included the following:

A. Plumbing Leak Repair

One large leak and several small leaks were found in welds in the plumbing module. Since they could not safely be rewelded, Stycast 1266 epoxy was painted into the leaks. This fix was successful.

B. Vent Line and LL Probe

The original insert in the dewar vessel vent line, carrying the long LL probe and T1, was replaced by one with a flexible vent line extension, a short LL probe and T1. It: (1) permitted the dewar to be filled nearly full (200 liters maximum) when in the launch attitude, and (2) permitted level monitoring of the liquid helium only between 125 and 200 liters. The configuration of the vent line and LL probe is shown in Figure 33, while Figure 34 is a schematic diagram of the DSS as it existed during TPE's VI and VII. The location and orientation of the new vent line entrance and LL probe is shown on the scale drawing of Figure 19.

C. New Porous Plug

The porous plug module was rebuilt with a new porous plug welded in place. The new plug is 1.27 cm diameter by 0.63 cm thick; nominal pore size 0.5 micrometers, filtration grade.

D. New Thermometers

T1, T5, and T6 were all replaced by new, calibrated germanium resistance thermometers. During final TA assembly one wire on the T1 feedthrough was broken, leaving T1 in a three-wire configuration. The temperature conversion program in the DAS used the original four-wire coefficients. T5 and T6, whose precision is more critical, are both in a four-wire configuration. T6 and H3 are pressed firmly against the downstream side of the porous plug. T5 is pressed against the liquid side of the steel plate into which the plug is welded.

E. Vacuum Gauge on TA Case

A laboratory type GPH-320B Penning vacuum gauge was connected to an unused port on the TA case to permit monitoring the pressure within the TA. As will be described, it furnished valuable information on the state of the guard vacuum and the constituents of the residual atmosphere. It was subsequently decided to add a permanent vac-ion gauge to the TA for use during prelaunch servicing.

F. Rebuilt V6 and V13

New stems and stem seals were installed on V6 and V13, both of which subsequently operated correctly.

IX. TPE VI

This TPE was started on July 23, 1982, which was as soon as possible following completion of the modifications described above, with a series of vacuum leak tests to verify the integrity of the reassembled apparatus. Under the pressure of the IRT development schedule the TA guard was not adequately evacuated, which led to certain test difficulties during this and the following TPE, as discussed below. In addition through procedural errors, air was introduced into the plumbing during this TPE, which compromised the results and led to the final DSS test (TPE VII).

Figure 35 is a schematic of the test configuration during the majority of TPE VI, that is, through the conversion and SHe performance measurements before divided flow was started. Figures 36 and 37 give a graphical summary of the first and second phases, respectively, of TPE VI and Table 10 is the index of major events.

Tilt angle data was collected during the TPE with the following angle definitions: launch attitude at 0° (more precisely -1°), upright attitude at 90° and inverted horizontal attitude at 180°. For consistency in this report angles will be presented with the same definitions as in previous TPE's: 0° is upright, 90° (more precisely 91°) is launch attitude, and -90° is inverted horizontal attitude.

A. Fill

Because a large supply dewar was not available from the LHe supplier, we were forced to transfer from several 100-liter supply dewars. The changeover from one SD to the next is not an efficient process and we have no system transfer efficiency data.

Since LL does not begin to register until the dewar is about half full, we had no direct monitor of the filling process. Therefore we did several things to attempt to understand what was occurring. First, we began the transfer operation with the dewar nearly upright so that T1 would indicate the start of LHe collection. Second, each 100-liter dewar was set on an accurate scale during transfer from it so that we could determine when it was empty. In fact, to prevent introduction of contaminants, such as dirt or frozen gases, into the IRT the LX' dip tube was kept about 2 inches from the bottom of the SD, making the weighing process somewhat questionable. Third, we monitored the TA vacuum continuously and learned that when cold gas was flowing in the TA fill plumbing, the measured pressure PV4 was greater than 10^{-4} torr, but when LHe was flowing PV4 dropped to about 10^{-6} torr or lower. Consequently PV4 was an important indicator of system behavior.

Chilldown operations began at 0830 on July 13, 1982, with $\theta = 54°$. Very soon frost began to form on the outside of the FR. We feared that the FR was damaged and that the apparent high heat conduction would prevent filling. At 0923 the cooldown was stopped, so that FR could be inspected. No mechanical anomalies were seen which would indicate physical contact between the fluid line and the FR outer shell and at 1015 a slow transfer was restarted. At 1420 T1 indicated that LHe was collecting (T1 read 4.048 K); simultaneously PV4 dropped from 5×10^{-4} torr to 4×10^{-6} torr. Almost immediately the frost on the FR began to melt, indicating conclusively that at the higher pressure there was enough gas conduction in the narrow gap between the fluid line and the FR outer shell to cause the frosting. When the contaminating gas cryopumped onto the liquid filled plumbing, the thermal insulation improved and the frost melted. It was apparent from these pressure and thermal effects that significant quantities of condensible air components, rather than noncondensible helium gas, remained in the TA and that the TA evacuation had been terminated prematurely. With the schedule pressure we were experiencing we decided to continue with the test rather than warm the system to room temperature and pump the TA vacuum for several more days. As will be seen later, this decision allowed us to gather a considerable amount of good data, but led to a termination of TPE VII earlier than would have been necessary.

At 1430 it was necessary to change to a new 100 liter SD. The changeover took about 12 min. θ was raised to 15°. Transfer from this dewar was rapid as indicated by the changing SD weight. PV4 fell as low as 8×10^{-7} torr. At 1546 PV4 rose rapidly and erratically to 2×10^{-5}, indicating that the SD was empty. Changeover to the third 100-liter SD took only 6 min. By 1730 LL had not yet registered the presence of LHe. We did not know whether LL was defective or we were transferring inefficiently, so we decided to terminate filling until the following morning. LX' was removed and V15(RV4) was installed on the FR. A 3.5 psi relief valve was connected to the outboard end of the vent line, so the LHe which had collected pressurized to 3.5 psi overnight.

In the morning of July 14, 1982, the dewar was slowly depressurized and tilted back and forth to determine the angle at which T1 was just immersed in the LHe. That angle was $\theta = 62°$. A new 100-liter SD was connected and transfer restarted at 0820. With $\theta = 75°$ at 0855 T5 and T6 temperature readout came on scale at 18.4 and 19.1 K, respectively. At 0910 T5 and T6 both read 4.5 K; changeover to a fifth SD was done at this time. At 1023 LL began to register LHe. Transfer rate was about 1 pound or 4 liters per minute. At 1030 this SD was empty and was removed. was increased to 90° to check the LL probe. Connection and startup of the sixth SD was accomplished at 1100. The DSS was oriented at $\theta = -91°$ (launch attitude) to verify procedures; this operature was straightforward. At 1115 with LL indicating 81% immersion, the DSS was raised to $\theta = 60°$ (LL probe $\sim$ vertical) to permit maximum dewar fill. This reduced LL to 37%. AT 1146 LL indicated 100%, so the SD was disconnected and the fill system was put into flight configuration. The vent lines and vacuum pumps were arranged so that during pumpdown the DSS could be rotated to various positive angles without binding of lines.

B. Conversion and Stabilization with SHe

Pumpdown was started at 1320 on July 14 with $\theta = 30°$. As the pressure and the liquid level slowly fell, the conversion process was stopped briefly several times by closing the solenoid valve on the vacuum pump. At each pause: the DSS was slowly rotated back and forth to determine the depth as a function of and to calibrate the three-wire readout of T1 by comparison with the vapor pressure in a static condition. A check of T1 was done just at the lambda point where it was determined that T1 was reading 74 mK low. At a later time, 7:15:0745 and lower temperature (1.7 K), it was reading 70 mK low. We assumed that the correction was 70 mK at all temperatures encountered below T_λ; henceforth, all values of T1 shown will be corrected upward by 70 mK.

A long term, essentially undisturbed SHe performance run was conducted as a continuation of the SHe conversion process, starting when the system reached T_λ on July 14 and ending on July 22. Figure 36 shows this period. System conditions were: $\theta = 90$ (approximate launch attitude); pumping via V5 as in TPE II. Conversion was done using RP1 which is a Leybold Heraeus S60 1000 liter-per-minute pump, but at 1425 on July 15 we substituted an S16, 400 liter-per-minute pump, like the one in the IRT Vacuum Maintenance Assembly.

Four calibrated flow meters were installed on the pump vent and tied into the DAS. Their ranges were: (1) F1; 0-5000 sccm or 0-43 mg/s; (2) F2; 0-1000 sccm or 0-20 mg/s; (3) F3; 0-10,000 sccm or 0-65 mg/s; and (4) F4; "0"-50,000 sccm or 40-230 mg/s. A cross check of the four meters was done at 1830 on July 15 at about the minimum flow rate observed: F1 = 4.04 mg/s, F2 = 4.11 mg/s, F3 = 3.85 mg/s, and F4 = 0 (below its minimum). The following day F4 was replaced by F5; 0-1000 sccm or 0-20 mg/s.

A significant disturbance in the test occurred on July 16 when we incautiously attempted to install and operate on the inlet (low pressure) side of the vacuum pump the prototype flight mass flow meter. Although it had been leak-checked several weeks previously and had been tight, the flow meter had a large leak. During the 38 min it was connected to the vent system, an undetermined quantity of air entered the cold plumbing. When the existence of the leak was finally established and the flowmeter was removed from the system, further checking revealed a very small vacuum leak at a connection to a mechanical pressure gauge. This leak had permitted air to enter the vent plumbing at a very low rate but for a long time (since pumpdown began on July 14). This leak was also corrected. The net effect of this air ingestion appears to have been a partial vent blockage, probably in the tube connecting the middle VCS to the inner VCS, and also on the porous plug.

The most apparent effects of this partial blockage were: (1) a large drop and slow (30 hr) recovery of the vent flow rate, (2) a significant increase and slow recovery of T2, and (3) smaller disturbances in T1, T3, T4, T5, and T6.

To assess the performance of the DSS during the stabilization period we have plotted on Figure 36 with dashed lines the corresponding behavior of T2, T3, T4, and F1 during the similar period of TPE II (Figure 9), referenced in time to the initial warmup of T2 on July 14-15. In spite of the flow and temperature perturbation discussed above, very similar behavior in the two tests is seen. The only basic physical difference in the DSS between the two TPE's is the attitude, upright in TPE II and horizontal (launch) in TPE VI.

In TPE VI T2 stabilized a little more rapidly and leveled off at 42 K, about 5 K and 14% warmer than in TPE II. T3 deviated at most 2 K from the TPE II curve, leveling off at an estimated extrapolated value of 98 K, 2 K and 2% less than previously. T4 consistently ran cooler by about 4-5 K than in TPE II, approaching a steady value of 182 K or 2% less. F1 began its initial rise much like TPE II. During the recovery from the flow perturbation it was as much as 0.75 mg/s or 14% high, but toward the end of this test it was approaching an estimated steady state value of about 8.7 mg/s which is only 4% higher than in the TPE II.

The liquid level during most of TPE VI could not be measured directly because of the short new LL probe. The actual volume remaining was therefore computed by hand by integrating F1, starting from the last measured level at 2210 on July 14. As a consequence, the rate of change of LL is not independent of F1, and cannot be used to verify the vent mass flow rate, as was done in TPE's II, IV, and V.

C. Porous Plug Gas Flow Test

At 1130 on July 22 with T1 = 1.79 K we attempted to connect the porous plug to the vent circuit by closing the plug bypass valve V5 tightly. F1 fell to zero and T5 and T6 began to warm. The flow did not recover as in previous plug flow tests and we concluded that the plug was totally blocked, undoubtedly by the frozen air contaminants discussed earlier. In the process of checking the system we discovered the small vacuum gauge line leak referred to previously and sealed it. We then attempted to warm the plug by means of heater H3. A current of 4 mA was passed through H3, generating about 98 mW, for 18 hrs. The heater current was then increased to 4.5 mA or 123 mW, the maximum level we judged to be safe from damage to H3. The valve actuator stem was also inserted in V5 to increase heating. The plug pores did not open up with all of these actions and the plug warmup attempt was terminated on July 23. The bath was allowed to recool until the morning of July 25 by pumping through the plug bypass.

D. Divided Flow Test

We decided to proceed with the divided flow tests on July 25 under the assumption that the steady state results with flow through the plug would not be significantly different from those with flow through the plug bypass. The system configuration was essentially as shown in Figure 14, where flow meter F3 was used in this test in place of F2 for the diverted (fill circuit) flow. At the time the divided flow test began it was estimated that about 10 mg/s flow would be required to properly cool the cryostat and optical system. As the test proceeded, our objective was to achieve 10 mg/s in F3 with a reasonable F1 and with a bath temperature $\sim$ 2 K. When the test started F1 was 7.5 mg/s, T1 sensor read 1.754 K, and a static pressure check indicated that the bath temperature was 1.714 K. Initially F1 was adjusted to 3.5 mg/s; F3 was 2.3 mg/s. Immediately T2, T3, and T4 began rising as expected. F3 began to increase immediately; F1 continued decreasing for a few hours, then began to increase. At 2200 on July 25 F1 was reduced again and the system was left alone for 48 hrs. On July 27 F1 and F3 were flattening out and appeared to be approaching steady values of about 6.0 and 7.5 mg/s, respectively. T2 had been essentially constant at 55 K for 24 hrs and T3 and T4 were leveling off more slowly.

At 2320 on July 27 a static pressure check of T1 was made. T1 was reading 8 mK warmer than the bath which was at 1.861 K. F1 was then reduced to about 4 mg/s; F2 was not adjusted. F1 and F3 began rising again as did the VCS temperatures and T1. Vent flows were not further adjusted for 58 hrs. F1 and F3 leveled off and the shield temperatures, particularly T3 and T4, continued rising. The steady values of F1 and F3 were 5.25 and 10.0 mg/s, respectively. The total flow rate corresponded to a boiloff rate of 0.38 liter/hr or 9.1 liter/day and a heat load of 354 mW.

E. End of Test

Because the blockage of the porous plug had prevented a satisfactory demonstration of space operation of the dewar and because of the strong pressure to complete this test series, we decided on July 30 to terminate TPE VI, attempt to clear the porous plug, and run another TPE to test the plug. Prior to stopping the divided flow measurement, we slowly raised the tilt angle to check the effect on the T1 readout caused by its height above the liquid level. With $\theta = 90°$ we estimated that T1 was about 17 cm above the SHe and it read 2.000 K, 88 mK warmer than the bath temperature which was determined by a static pressure measurement. θ was raised in 2.5° increments; T1 fell by about 15 mK with each decrease in height. At $\theta = 75°$ T1 reached 1.923 K and cooled no further, it then being 11 mK warmer than the bath. This suggests that the 70 mK correction applied to T1 throughout this TPE because of its three-wire configuration may have gradually changed to about 60 mK.

The DSS was then raised to the vertical and the remaining liquid helium blown out of the dewar by applying a slight GHe pressure through the vent line and allowing the liquid to flow out of the fill line into the room, where it evaporated. A warm GHe purge was then started to warm the plumbing, porous plug and shields to 100 K or above to melt the contaminants. By 0700 on July 31 we judged the internal components to be warm enough, stopped the purge, and began to evacuate the plumbing.

On August 2 the plumbing was repressurized to ambient and gas flow tests performed. The lines, and especially the porous plug, were found to be clear. Plug gas flow was as expected from previous room temperature measurements.

F. TPE VI Conclusions

At the end of this TPE the following conclusions could be drawn:

1. Previous repairs and modifications to the TA hardware were leak tight and otherwise successful.

2. The TA was not evacuated for sufficient time prior to starting this TPE and a significant contaminant pressure existed within the TA. However, because it consisted only of condensible species, it did not impact this TPE, once the plumbing was cold enough to freeze the gases.

3. A sensitive vacuum gauge to measure the TA pressure provides valuable data on the state of chilldown and fluid transfer, which is all the more valuable (a) when the dewar is filled in the launch attitude and T1 is not immersed in liquid until the dewar is one-half full and (b) because the new liquid level probe also does not begin to register at all until the dewar is one-half full. From this conclusion it was decided to include a vac-ion gauge on the flight system to provide TA pressure data during prelaunch cryogen servicing.

4. It is crucial that great care be taken to keep air and water vapor from the plumbing interior, to avoid disastrous blockage of the porous plug and the vent lines as occurred in this test. Previous TPE's have shown that this can be accomplished during normal fill and topoff operation and during low-pressure evacuation and test. However, connecting and disconnecting lines during low-pressure helium servicing will still require special attention and care.

5. If air blockage of the porous plug does occur, the dewar can be emptied and warmed and the contaminants pumped away in as little as 3-days. To provide for this eventuality a special contingency procedure should be written and processed through the Safety Office and KSC.

6. Steady state performance with superfluid helium and in the launch attitude is essentially identical to that measured with the system upright.

7. Divided flow results were consistent with those obtained in TPE's II and IV. With 10.0 mg/s flowing to the simulated cryostat the total boiloff rate was 9.1 liter/day. At that rate 125 liters of SHe would last 13.7 days and 200 liters, 22 days.

8. If the T1 sensor is out of the SHe bath, it reads somewhat warmer than the bath. However, the discrepancy is probably less that 0.1 K and T1 is a useful monitor of the bath temperature.

X. TPE VII

This concluding TPE of the series was started in the afternoon of August 5, 1982, as soon as a 500-liter supply dewar of LHe could be delivered to the laboratory. The VCS's were still warming from TPE VI and were approaching room temperature. The main objectives of this test were to verify the gas flow and liquid control characteristics of the new 1.27 cm diameter porous plug and to determine the effect of the plug heater. These objectives were 15, 16, and 18 (Table 2). All were successfully completed (Table 3) as well as several others which had been concluded earlier, notably number 11, "System Performance with SHe, Tilted," which was done for the first time with the porous plug continuously in the vent circuit, and number 8, "Verify Prelaunch Operations," which more fully exercised some of the servicing procedures than was possible in TPE VI. It should be noted, however, that we were still unable to conduct any of the low-pressure servicing tests (objectives 6 and 7).

Table 11 is a summary of the major events during the 13-day test and Figure 38 is a graphical summary of the majority of the TPE's. The configuration was essentially as in Figure 35. The system was tilted to $\theta = 30°$ to permit maximum fill. The initial TA guard pressure (PV4) was 7.4×10^{-4} torr. A depth probe was installed in the SD to measure its volume during transfer.

A. Fill

Slow chilldown of the DSS was started at 1730 on August 5 with an SD pressure of 4.5 psi. As in TPE VI the fill receptacle frosted until liquid began to collect in the dewar (at 2000); PV4 then fell to 3×10^{-5} torr and the ice melted. Approximately 90 liters of LHe were used to precool the system. When liquid collection began, the SD pressure was raised to 4.9 psi and the LX valve opened fully. The transfer rate was about 3 liters/min and, since we were using a 500 ℓ SD instead of the several 100 ℓ SD's of TPE VI, filling was smooth and continuous. PV4 gradually fell into the mid 10^{-6} range. At 2108 the LL probe began to register and at 2140 LL registered 100%. Due to the very asymmetrical geometry of the dewar when tilted to 30°, it is difficult to estimate the actual amount of LHe present when LL = 100%. A rough guess would be 220 liters. Based on a transfer rate of 3 ℓ/min and a collection time of 100 min, a total of 300 liters was transferred from the SD during liquid collection. A total of 390 liters was used for the entire cooldown and fill operation which took 4 hrs and 10 min, exclusive of the time required to connect and disconnect the external apparatus.

The system was secured for the night with V15(RV4) installed on the fill receptacle but with V7 open to prevent any possible reverse pressure on B1. A 1 psi relief valve was mounted on the outboard end of the vent line.

B. Conversion to SHe

On the morning of August 6 the vent lines were checked for vacuum leaks and pumpdown to SHe was started at 0715. At this time LL showed 8% or 4.0 cm and the system was rotated to 0°, the depth then measuring 9.5 cm and 24%. After 2 hrs, θ was raised to 13° to keep T1 wet.

At 0930 with T1 = 2.8 K and PV1 = 145 torr the porous plug bypass valve V5 was closed so that we could determine whether pumpdown from temperatures well above the lambda point could be accomplished via the plug. Such a condition could occur during prelaunch operations, if electrical power for the vacuum maintenance assembly were turned off for a long time and the SHe in the dewar warmed to above T_λ. When V5 was first closed, T5 and T6 were 6.5 K and 5.2 K, respectively, and the vent flow rate was greater than 300 mg/s. The flow rate fell to a few mg/s and T5 and T6 began cooling slowly. By 1040 the plug was cooling rapidly and the flow rate was rising. At 1044 T5 and T6 both cooled low enough (5.5 K) that the temperature conversion algorithm came in range. The flow rate became so great that gas was hissing audibly from the flow sensor outlet. While this plug flow test was in process, several calibrated flow meters with different ranges had been connected in series to the vacuum pump exhaust to provide a broad flow rate coverage without the need for further hardware changes. We incorrectly assumed that the hissing meant there was a problem and opened V5 for about an hour, during which the bath cooled to 2.5 K, the plug warmed to 15 K, and the flow rate decreased smoothly to about 150 mg/s.

When V5 was again closed, the plug cooled in 2 min from 15 to 2.9 K, slightly warmer than the bath; the flow rate dropped somewhat but immediately recovered; and the bath continued to cool, but at about 2 mK/min rather than the 4 mK/min rate with V5 open. Through this period PV4 was $\sim 1 \times 10^{-7}$ torr.

V5 was later opened for 2 hrs to hasten the cooldown, but at 1515 on August 6 it was torqued closed to 9 inch-pounds and left in this condition throughout the majority of this TPE (until August 13). Note that all gas and liquid flow was then under the passive control of the temperature dependent plug impedance. V7 and V17, both of which had been closed finger tight, were also torqued closed to 9 inch-pounds, all three cold valves then being in their flight configuration. The bath was allowed to cool for 3 more hours, at 1815 T1 = 2.15 K.

Starting at 1815 on August 6 the remainder of the cryogen system of the DSS was put into the flight configuration. The valve operator cover and other flight hardware not affecting the cryogenic tests were not installed. First, V15(RV4) was locked into the FR and, for the first time in this TPE series, the line between cold V7/B1 and the warm valves V15(RV4) was evacuated. We had been concerned in prior TPE's that the helium gas column between V7 and the warm end contributed a significant heat load into the TA. The fill circuit was then in its flight configuration.

Second, the GSE vent line was removed from the VR and all subsequent venting was done via the flight vent connection on the TA. V16(RV3) was locked into the VR. As additional insurance against air leakage, V13 was left closed, but otherwise the TA vent plumbing was in its flight configuration. Third, a flexible vent line and roughing pump system was connected to the permanent TA vent line termination, carefully checked for gross vacuum leaks, and used in the following performance measurements. At this point the system configuration was as shown in Figure 39.

In preparation for the performance tests during which LL would not be immersed and could not furnish liquid volume data, we planned to continuously integrate the flow meter data to keep track of the fluid volume. To attempt to establish an initial condition we tilted the system to -36° and allowed the fluid to settle down (which took more than 10 min). The measured depth on LL of 1.55 cm was later concluded to correspond to 96 liters of SHe. At the time, however, a volume of 109 ℓ was assumed as the starting condition. Figure 40 shows the calculated fluid volume from that point on.

C. SHe Performance Test

There were two fundamental differences between the superfluid performance sequence discussed below and the previous tests. First, we were able to accomplish a fairly comprehensive set of measurements of liquid control behavior of the porous plug

with a reasonable net heat load, which was much less than that encountered during TPE V. As a result, the plug data are somewhat different. Second, since V5 was closed all the time, the system had to move from one state to another with the temperature dependent flow characteristics of the porous plug influencing the rest of the parameters. The result of this situation, as will be discussed in detail later, was that temperatures and flow rate participated in a damped, coupled oscillation, not seen previously. First, we will consider the general system behavior during the test from 08/06/0815 to 08/09/1400, then look in detail at the porous plug data. Finally, we will consider the anomalous behavior after August 11.

Through August 6 and the early part of August 7 while the first porous plug measurement was in progress a number of tilt angle changes and valve changes were made. Nevertheless the bath cooled monotonically and the three VCS's cooled, reflecting the flow rate of around 50 mg/s. At 1540 on August 7 the plug went dry and remained dry but cool (T5 MAX = 11.7 K) until 08/09/1400. T2 went through minima of 38.5 and 61 K, respectively. All three then began to increase. Meanwhile F1 began to decrease in response to the reduced heat load from the cooler inner VCS (T2), and T5 rose as F1 fell. As T2 rose, the cooling rate of the bath slowed and reached a flat minimum of 1.813 K at 1800 on August 7, then rose to and fell off at 1.900 K. By midnight on August 7 F1 had fallen to 0.6 mg/s, T5 had risen to 11.7 K, and T2 was 41.6 K and rising. During the night the DAS hung up and no data were recorded of the rapid recovery which must have occurred, but at 0800 on August 8 the flow was 6.5 mg/s and rising slowly toward a maximum at 1300, T5 was cool (2.7 K), and T2 was again falling. The dotted lines on Figure 39 show the probable values during the data outage. T2 and F1 then each went through a second, smaller minimum and again began rising, T2 bending toward an apparent second minimum. Under pressure of the test schedule we decided not to wait for the system to complete another cycle. At 1400 on August 9 we disturbed the system and started a new plug performance sequence.

The behavior of the system just described seems clear, and is explained as follows. With the porous plug dry but cold its temperature-dependent impedance to helium gas flow dominates the vent process which is driven in turn by the vapor pressure of the liquid helium bath. More exactly venting is driven by the pressure drop ΔP across the plug, but for reasonable flow rates and unrestricted vent line pumping, ΔP is essentially the bath vapor pressure at T1. Initially in the process the plug was wet by liquid and the flow rate was high. As a result the bath was cooling and the VCS's were very cold. Because the bath was approaching a steady state temperature, the flow rate began to decrease and the VCS's began to warm. At 1540 on August 7 when the plug went dry, F1 was 6.9 mg/s and T1 was 1.815 K. T5 immediately increased by 0.8 K and then steadily warmed. In response F1 immediately fell to 4.2 mg/s and then steadily fell further, reaching its minimum of 0.6 mg/s at about midnight on August 7 when T5 had warmed to 11.7 K. At the moment the plug

dried out the external vent line pressure was 4.4 torr and the bath vapor pressure was 13.2 torr; ΔP was thus 8.8 torr. With the slow rise of T1 in response to the increased heat load from the IVCS (T2) and the reduced evaporation, the plug ΔP began to increase. At the data system drop out (flow minimum) T1 was 1.855 K, and the measured plug ΔP was 13.4 torr and increasing. Now in spite of the plug's higher temperature the flow began to increase under the higher pressure bringing more cooling to the plug. By the time the data system was restarted the plug was at 2.8 K, F1 had jumped to 6.5 mg/s and the IVCS was cooling again.

Over the next 30 hrs the system went through most of another cycle. By inspection of Figure 38 we conclude that if the system had been left alone for a few more days the oscillations would have damped out leaving the system in a steady state gas flow condition with the following approximate values of the parameters: T1 = 1.9 K, T2 = 39 K, T3 = 90-95 K, T4 = 180-190 K, F1 = 5.5 mg/s, and T5 = 3 K. What is surprising is that while T2, T3, and T4 approach the same values that were seen in TPE II (Figure 9), F1 is about 30% lower and the calculated system lifetime that much greater. One hundred twenty-five liters would last 38 days and 200 liters would last 61 days (without flow diversion to the cryostat).

D. Porous Plug Performance Tests

Two separate porous plug fluid control measurement sequences were conducted, the first shown in Figure 41 from 08/06/1900 to 08/07/1600, and the second, shown in Figures 43, 44, and 45 from 08/09/1400 to 08/12/0110. With the new vent line in the dewar it was necessary to invert the system to negative angles in order to keep the vent line entrance immersed in liquid. When the first test began there were 96 liters in the dewar and when the second test ended there were 62 liters remaining. From Figure 19 we estimate that with 96 liters the DSS had to be rotated to about -64° to bring the vent line entrance to the SHe surface, and to -98° to pour bulk SHe over the apex of the vent line where the new section connects to the old. At this latter angle the hydrostatic head of SHe on the porous plug would be 12.5 cm or 1.32 torr. Note that with $\theta > -98°$ (more upright) there would be a vapor gap in the vent line between the bath and the plug. The more upright the system or the lower the liquid level, the longer the vapor gap. We assume that the liquid at the porous plug is continuously replenished by vapor condensation from the bath, as discussed in Section VII.C.1. With 62 liters the corresponding angles for vent line immersion and continuous liquid in the vent line were approximately -85° and -110°, respectively, and the head at -110° was 29 cm or 3.1 torr. Recall that at negative angles the fluid trap in the TA is inverted, does not inhibit fluid flow into the TA at appropriate angles, and retains a small amount of fluid (out of contact with the plug) when the DSS is rotated from high negative angles back to the inverted horizontal.

1. First Tilt Test

This sequence began (Figure 41) when the external vent control valve Ve was closed and the dewar contained 96 liters of SHe, the DSS was rotated to -75° and Ve was then opened slightly. The porous plug was at about 12 K with the bath at 2.15 K. Although the porous plug was about 38 cm above the bath level, the vent line entrance was well immersed in the fluid, as shown in Figure 42a. Very quickly the flow rate rose from a few mg/s to more than 50 mg/s, the bath began cooling, and the plug cooled in 40 min to less than 2.1 K. Note that T5 was about 3 mK cooler than T6 and remained so throughout much of this tilt test, except (a) when the system was tilted to -10° for 40 minutes), (b) when the venting was stopped (SV closed), and (c) after 0630 on August 7. While the tilt angle remained at -75° the plug temperature was somewhat unsteady. The system was raised to -10° to lift the vent line entrance out of SHe. It was later seen (Figure 42a) that the minimum angle for this to occur was -65°, so at -60° the vent was also exposed to vapor only. During this raised period, the plug warmed a bit.

When θ was again increased to -65° and thence incrementally to -100°, the plug became quite cold, then warmed, remaining colder than the bath until 2210. The vent line solenoid valve (SV) was closed for two periods to simulate shutdown of the VMA during prelaunch operations. Both times the bath warmed slightly and the plug, where the primary evaporation process takes place during venting, warmed considerably (although never above 3.3 K). The SV was closed for a total of 50 min during a 66-min period. T1 rose from 2.111 to 2.116 K, only 5 mK. At this rate (1 mK/10 min) the bath would not have reached T_λ for an additional 560 min or 9+ hrs. This estimate is somewhat optimistic, since the VCS would warm without flow and the bath heating would increase. Nevertheless a conservative average warming rate might be 1 mK/3 min or 20 mK/hr. Starting from a pump shutdown at say 2.0 K the system would not reach T_λ for more than 8 hr. Furthermore, it is not obvious that the plug would lose control of the liquid even if the bath temperatures exceeded T_λ. Depending on the hydrostatic head and other factors, the plug was as much as 96 mK cooler than the bath (0630 on August 7, Figure 41).

At 2350 on August 6 with θ = -100° (Figure 42b) the hydrostatic head was 16 cm or 1.7 torr, the vapor gap in the vent line was very short, and the plug (T5) was 8 mK cooler than the bath. When θ was raised to -90° at 0020 on August 7, the liquid fell to 7.4 cm below the plug and the vent line was almost entirely above the liquid level, making the vapor gap quite long (Figure 42b). The bottom of the trap, however, held a small pool of liquid. T1-T5 jumped to 38 mK, reflecting the much longer vapor transport distance. The flow impedance of the vent line required a larger ΔT to drive the mass transport.

As the bath level slowly fell, the ΔT increased. The plug, isolated from the bath by the fluid in the bottom of the trap, was being supplied from an essentially constant source in the trap. At 0700 on August 7 the plug ΔT and plug-bath ΔT both began to change. From Figure 42c this appears to have occurred just when the fluid level fell low enough that vapor could flow all the way from the bath to the plug. At the same time F1, which had been falling steadily, dropped abruptly. Until about 0840 some liquid remained in the bottom of the trap, T6 remained warmer than T5 (now by more than 30 mK, instead of the previous 3 mK), and T5 began slowly to approach T1. At 0830 the plug ΔT began to reverse itself. T6 fell 20 mK and remained less than T5, which rose 15 mK to within 30 mK of the bath and continued to approach T1 until the plug warmed abruptly at 1430. At 1230 the plug ΔT again reversed sign. T6 became 50 mK warmer than T5, accompanied by another rapid drop in F1, and remained essentially constant until the dryout. At that time F1 again fell quickly (from 6.9 to 4.1 mg/s), then decreased further as the bath began to warm. Based on the calculated depth of SHe in the system, it appears that the changes in the plug temperatures and flow rate after 1220 accompanied the evaporation of the last fluid from the bottom of the trap.

2. Second Tilt Test

This tilt test, which lasted 2 1/2 days and is covered in Figures 43, 44, and 45, started at 1400 on August 9. As the system was being set up, there were four brief and different behaviors which we will discuss next. Then at 1715 the final tilt angle setting was made and the long undisturbed test began.

When the tiltover from -55° began the bath had been at 1.90 K for more than 24 hr and the IVCS and flow rates were leveling off. F1 was 5.3 mg/s. T5 and T6 were 3.2 and 3.3 K, respecvtively. With about 74 liters of SHe in the dewar the minimum angle for immersion of the vent line entrance was -75°, and that for pouring fluid over the apex of the vent line was about -107° (Figure 46a).

As tilting progressed incrementally, no patricular behavior was seen as θ passed -75°. Not until θ reached -110° did the system begin to respond appreciably. Suddenly T5 and T6 dropped to near the bath temperature, showing that liquid had reached the plug, T1 began rising at about 0.7 mK/min, and F1 jumped to more than 25 mg/s. Throughout the warming period at large tilt angles T5 remained <T6 but both were very erratic. The fluid entering the TA initially had to cool the mass of somewhat warmer plumbing and some may have passed through the porous plug under the higher hydrostatic head (Figure 46a).

At 1550 θ was returned to -40° to check the T1 reading, and SV was closed briefly. After SV was reopened, T1 began cooling and T6 became much cooler than T5.

At 1630 θ was again tilted to -115° and briefly to -120°, then held at -95°. Figure 46a shows the very large hydrostatic heads. At the greater tilt, T1 again increased, and T6 was warmer than T5.

Finally, at 1715 θ was set at -97.5° and the system was allowed to stabilize undisturbed for 23 hrs. Initially the hydrostatic head was only 5 cm or 0.6 torr, T1 was 1.930 K, T5 was 50 mK cooler than T1 (ΔT_{DEWAR} = 50 mK), and T6 about 55 mK warmer than T5 (ΔT_{PLUG} = -55 mK). As the system sat undisturbed and the flow rate (and LL) fell, ΔT_{DEWAR} decreased to 18 mK, while ΔT_{PLUG} increased in magnitude to -140 mK.

At 1545 on 08/10 θ was increased from -97.5° to -100° (Figure 46b). T6 fell immediately so that ΔT_{PLUG} = -72 mK. F1 rose from 6 mg/s to 6.8 mg/s. T1 and T5 changed only slightly, so ΔT_{DEWAR} = 20 mK. With no further changes for the next 17 hrs T6 again gradually increased until at 0900 on August 11, ΔT_{PLUG} = -101 mK. ΔT_{DEWAR} = 20 mK and F1 = 6.75 mg/s. Figure 46c shows the approximate fluid level.

From 0910 to 1015 θ was incrementally increased to -106° (Figure 46c). As before F1 rose and T6 fell (ΔT_{PLUG} = -12 mK). This time both T1 and T5 increased by about 10 mK. Then at 1150 T6 began rising much more rapidly than previosly. Later (1530 hours), following a plug heater test to be described below, θ was increased to -110° and the behavior just described was repeated, T6 then leveling off at 1.85 K so that ΔT_{PLUG} = -140 mK. Finally at 0110 on August 12 the plug dried out, ending this plug liquid test.

E. Porous Plug Heater Test

From 1323 to 1420 on August 11 the effect of the 6000 Ω porous plug heater H3 on the plug operation was measured. Initially the heater was energized for short times with increasing currents. Each time T6 warmed momentarily, but no other parameters responded significantly. For example, when 4.67 mA was applied for 60 s for a power of 130 mW and a total energy of 7.8 Joules, T6 rose from 1.832 to 3.452 K at the end of the 60 s, then fell to below 2.0 K within 60 s. T5 did not change, while F1 rose 5% and immediately fell to its pre-heat value.

At 1356 H3 was energized to 130 mA and left on for almost an hour, as seen in Figure 45. T6 rose to 3.606 K in 2 1/2 min, slowly fell to 3.44 K in 5 min, then rose slowly and unsteadily, held at 5.2 K for 12 min. Meanwhile F2 had fallen in response to the T6 rise, and T1 and T5 rose slowly as a result of the reduced mass flow. AT 1448 T6 suddenly rose to 10 K and F1 fell to 0.75 mg/s. The heater was de-energized at 1449 and T6 fell below 2 K within 2 min, accompanied by a rapid rise in F1.

It is not clear how the plug would have responded if the downstream side of the plug had been wet with SHe when H3 was turned on, but its effect with vapor in the plug was to shut down the venting. This is the opposite of the effect we had anticipated and what in fact may occur with a fully wet plug. We had expected that the superfluid component in the plug would be drawn to the warm heater and there evaporated, increasing the dewar mass flow rate without increasing the bath temperature. We must look for this effect in later operational tests. In any event H3 did not cause any irreversible deleterious effects and the vent process recovered immediately from its operation.

F. End of Test

Following the end of the second plug performance tests the system exhibited a new behavior, caused by the presence in the TA guard vacuum of cryogenically trapped contaminants, and the system boiloff increased dramatically. At this point in TPE VII we planned to remove the DSS from the flight support structure so that final experiment assembly could begin. The DSS was to be placed in the fixed table in which TPE's I and II had been conducted and then allowed to complete its transition to a steady state condition, hopefully via the damped oscillations discussed earlier and seen in Figure 38.

When the porous plug went dry after midnight on August 11 (Figure 45) the mass flow rate fell to less than 0.5 mg/s, accompanied by a warming of the plug to more than 18 K. More significantly, the reduced flow rate allowed the IVCS to warm to 51 K by 0645 on August 12, and the other shields warmed as well. The system was tilted further to recool the plug, increase the flow, and, hopefully, regain control, but at 0800 it was necessary to rotate the DSS upright for removal from the rotation support stand. Removal required cessation of venting for several hours, so we started a deliberate 4-hr shutdown to simulate a prelaunch VMA shutdown. During this time the IVCS warmed further, and it continued to rise at about 2 K per hour after pumping was again started, due to the low flow rate.

The last personal observation was made at 1500 and the system was left for the night. Prior to 1700 PV4, the TA vacuum pressure, was less than 6.2×10^{-6} torr. At 1700 the IVCS temperature reached 66.0 K and several things happened: first, the cryopumped nitrogen on the IVCS evaporated, raising the internal pressure 2 orders of magnitude to 6×10^{-4} torr; second, the IVCS cooled very slightly due to the evaporation and immediately began warming at a rate of almost 2 K in 5 min, an order of magnitude faster than before 1700; third, the bath heating rate increased by an order of magnitude and it soon exceeded T_λ. At this point the system was in a self-induced warmup caused by the sudden increase of gas conduction heat transfer in the TA and the fact that venting was now only by gas flow through the porous plug. If the high heat load could have been stopped, the system would have recovered rapidly. As it was,

the system did begin to recover on its own, confirming our general understanding of the system operation. As the vapor pressure of the warming LHe increased, the gas flow through the plug increased, and at 1945 it stopped warming and began cooling. Now F increased more rapidly, finally reaching 50 mg/s; the VCS's all began cooling and the bath warming rate slowed, then reversed. Recovery continued unaided until 1345 on August 13 when we decided to try to cool the plumbing faster in order to recondence the TA contaminants, so that the system could be left alone over night. V5 was then opened, and F and the cooling rate increased considerably. T1 fell from 3.44 to 2.20 K in 2 1/2 hr. At 1435 PV4 suddenly dropped from 6×10^{-4} torr to 2×10^{-5} torr and then fell in 1/2 hour to the mid 10^{-6} torr range, showing the recondensation of the gaseous contaminants. At 1435 T2 = 33.8 K, T3 = 69.8 K, and T4 = 122 K.

By this time less than 30 liters of liquid remained in the upright dewar. AT 1610 V5 was again closed and the system was left for the night. Unfortunately the warmup and contaminant release of the previous night repeated itself. By the time we had recooled the bath the next morning less than 10 liters remained, so we decided to terminate the test. The dewar went dry at about midnight on August 15.

G. TPE VII Conclusions

At the end of this final TPE the following conclusions were drawn:

1. The cleanup of the contaminants from the porous plug and cold plumbing, ingested during TPE VI, was successful, as were the procedures used during filling to prevent new air/water vapor from being introduced into the plumbing.

2. Filling of the DSS from a single, large SD was considerably more rapid and efficient, as expected, than from the several 100-liter SD's used in TPE VI.

3. The system could be put into the flight configuration quickly and easily, and filling and conversion to SHe in a simulation of prelaunch operations was conducted very successfully, including performing part of the conversion and all of the stabilization by pumping only through the porous plug.

4. Evacuation of the fill line between V7 and V15(RV4) was straightforward and probably contributed to the apparent improvement in performance by removing the gas conduction heat path within the fill line.

5. Closure of the three cold valves (V5, V7, V17) to a 9 inch-pounds torque apparently provided adequate force to give repeatable superfluid tight sealing. Until indicated otherwise this maximum closure torque will be observed in the system for all tests and operations.

6. The porous plug worked well as a liquid/vapor phase separator. Its behavior was generally explicable. Plug operation was measured under a variety of conditions including high positive and negative hydrostatic head situations that will not occur in flight, and near-zero hydrostatic head situations that were generally like those which will occur on-orbit. The on-orbit simulation was confused by the fact that the liquid level after conversion was low enough that to get a reasonable volume of SHe down the curved vent line to the trap and the plug required such a large tilt angle that the resulting hydrostatic head drove fluid completely through the plug. Then when the system was tilted back to reduce the hydrostatic head to nearly zero, the vent line contained a rather long vapor column connecting the plug and trap to the bath. As a result of this last condition, fairly large ΔT's developed between the plug and the bath.

Although the plug worked well throughout these situations, the actual space conditions were not well simulated. In space we would expect the vent line to be filled continuously with either bulk SHe or a thick film, either of which should serve to keep the bath and porous plug temperatures closer together. In the absence of gravity there will be no hydrostatic head. Even during RCS firings the body forces on the fluid will be quite small.

In summary, based on the results of this TPE, the porous plug should work quite satisfactorily during the mission.

7. The test of the porous plug heater was only partially conclusive. We expected the heater to increase the system mass flow by drawing extra fluid through the plug and evaporating it. This was, and still is, thought to be the effect when the porous plug is full of liquid. The heater was operated, however, when the fluid/vapor interface had withdrawn into the plug, and slightly warmer (130 mK) gas was exiting from the downstream side. As a result, the gas warmed even further and eventually the plug warmed enough to block gas flow and nearly stop the dewar venting.

We must attempt in later system tests to operate the heater when we have achieved a completely wet plug, even though such a condition may not occur during normal on-orbit operations. If the plug does not stay wet, then H3 will probably have no useful function during the mission.

XI. Summary of TPE Series

In addition to the many conclusions stated at the end of each individual TPE section, other system performance information can be extracted from the entire set of data and figures. Specifically we wish to predict the on-orbit behavior of the cryogenic system and to determine deficiencies in the information in order to plan for the complete experiment cryogenic acceptance test.

A. Steady State Temperatures

There are six temperatures of interest in the Dewar Subsystem, T1 through T6. Once the liquid helium is converted to superfluid, T1, the bath temperature and T5 and T6, the porous plug temperatures, will probably remain between $T_{\lambda} = 2.172$ K and the minimum temperature seen so far, 1.6 K. They may vary considerably (and relatively slowly) in this range, however, as seen in several of the earlier figures. The three VCS temperatures, T2-T4, are plotted in Figure 47 as a function of steady state dewar mass flow rate. Both dedicated flow and divided flow results are included. Except for the lower flow rate data points for TPE VI, which were excluded from the linear curve fits, the temperatures are linear in dewar flow rate. T2 is particularly insensitive to steady state flow rate and will probably run between 35 and 40 K on-orbit.

B. Steady State Flow Rates

The dewar and cryostat flow rates, F1 and F2, respectively, will be the parameters over which we will have partial short-term control, through adjustments of commandable valves V1 and V2. We can see from the system response in, for example, Figure 16 events D' and D'', that when a vent valve setting is changed during single (not divided) flow operation, there is an immediate corresponding change in the effected F, but as the system moves toward a new steady state over a period of many hours, the flow rate will recover and end up at a value not greatly different from what it would have been if the valve change had not been made. This suggests that rapid variation in internal flow conditions can be made, but to maintain the new higher or lower flow will require further valve adjustments.

Divided flow adds a further complication as seen in, for example, Figures 15 and 37. When one vent valve is changed, its flow is altered abruptly, but then both flows relax slowly over a long period. Achieving a particular steady "cryostat" flow might be difficult and require a long time, if the flow control valves had continuous adjustment capability. Unfortunately, the IRT flight valve system, V1 and V2, permits only a few discrete impedance settings, so that fine adjustment of a particular flow, dewar, or cryostat, may not be possible. This situation will be more completely explored during IRT System Verification.

It is interesting to consider quantitatively how the divided flow process operates in order that we can determine what the system lifetime will be when we dedicate the necessary cooling to the infrared optical system in the cryostat. This is, after all, the primary function of the entire cryogenic system of IRT. Figure 48 summarizes the steady state system flow rates as a function of the ratio, s, of the dewar flow to total flow. Thus when $s = 1$, all venting is via the dewar VCS and for $s = 0.5$, half of the total flow cools each of the subsystems. Recall that TPE's I, V, and VII were with single flow only ($s = 1$), the conductive heat

load was excessive in TPE's IV and V, and TPE I was with LHe only. Hence the scatter in the data. The large error bars on some data points reflect the fact that extrapolations to steady state flows were made.

The curves plotted in Figure 48 show the predictions of an earlier analysis of the IRT cryogenic system [1]. The experimental data verify the analytical trends qualitatively and, to a fair degree, quantitatively. Dewar flow is optimum at s = 1. As cooling gas is diverted to the separate sink (the cryostat) and is unavailable for refrigeration of the dewar VCS, those shields must shift to a new set of warmer temperatures. With the dewar IVCS (T2) now warmer the heat input to the SHe is increased and the total mass flow increases. Some of the increase supplies the cryostat and the remainder contributes to the dewar VCS cooling, thus limiting the rise in shield temperatures and fluid evaporation. Each set of points in the figure at a given s reflects a self-consistent steady state condition in a very complex thermal system.

APPENDIX A

SHe/LHe Performance Comparison

There are several factors which contribute to the increased efficiency of a dewar when it contains superfluid, rather than normal, liquid helium.

First, the density of SHe is about 0.145 g/cm^3 over the entire temperature range below T_λ, 16% greater than that of LHe (0.125 g/cm^3) at its normal boiling point (NBP) of 4.2 K and 1 atmospheric pressure. Consequently a greater mass of helium is contained in a given volume.

Second, the heat of vaporization of SHe in the temperature range 1.6 K to T_λ lies between 22.6 and 23.2 J/g, averaging about 23.0 J/g, compared with that of LHe at its NBP (20.6 J/g). So for a given heat load to a given mass of liquid, SHe will evaporate 12% more slowly than LHe, and for a given heat into a given volume of liquid, SHe will evaporate 29.5% more slowly.

Third, as discussed in Section D.1, more than 99% of the cold GHe evaporated from SHe exits the dewar and is available to cool the VCS; whereas, only 85% of the GHe from LHe at the NBP exits the dewar because of the high vapor density at 4.2 K.

Finally, if we examine the amount of cooling available at a 30 K inner vapor-cooled shield from the venting gas, we find that gas warming from 4.2 K has available enthalpy ΔH of 140 J/g, while that warming from 2.0 K has about 146 J/g, a 4% increase in cooling capacity.

Table A1 summrizes this information and shows that, all else being equal, we can store 16% more mass, for 29.5% longer lifetime, with a 5% lower vent flow rate and essentially the same shield cooling rate. Of course, there are several second-order effects which will modify these results somewhat, but the lifetime advantage of using SHe is clear.

REFERENCE

[1] Cryogenic Sub-System Performance of the Infrared Telescope for Spacelab 2. G. R. Karr, et al., in _Proceedings Eighth International Cryogenics Engineering Conference_, Geona, 1980, p. 38.

TABLE 1. CHRONOLOGICAL SUMMARY OF DEWAR SUBSYSTEM TPE'S

TPE #	DATES CONDUCTED	LIQUID HELIUM CONDITION FILL/OPERATE	SPECIAL CHARACTERISTICS
I	11/06/81 - 12/15/81	LHe/SHe	Work Table/Upright. SHe briefly at end. Limited data records.
II	12/23/81 - 02/11/82	LHe/SHe	Work Table Upright. V6, V13 Removed/Capped. Move to FSS in RSS at end.
III	02/11/82 - 02/12/82	LHe	RSS/Upright. V6, V13 Capped. Lost all liquid.
IV	02/22/82 - 03/09/82	LHe/SHe	RSS/Upright. V6, V13, Capped. Divided Flow.
V	03/09/82 - 03/29/82	LHe/SHe	RSS/Tilted. V6, V13 Capped.
VI	07/13/82 - 08/04/82	LHe/SHe	RSS/Tilted. New Vent Line and LL Probe. V6, V13 Operational.
VII	08/05/82 - 08/18/82	LHe/SHe	RSS/Tilted. New Vent Line and LL Probe. V6, V13 Operational.

TABLE 2. LIST OF TPE OBJECTIVES

1. Verify that the DSS operates safely in the upright attitude both (a) normal and (b) superfluid helium, including verifying the superfluid tightness of the liquid vessel.

2. Verify that the DSS operates safely in the tilted attitude with superfluid helium, including verifying the superfluid tightness of the TA plumbing.

3. Verify proper operation of the instrumentation, breadboard and DAS.

4. Verify LHe (a) fill and (b) topoff procedures.

5. Verify SHe conversion procedures.

6. Verify low pressure (a) fill and (b) topoff procedures in the upright attitude.

7. Verify low pressure (a) fill and (b) topoff procedures in the launch attitude.

8. Verify the proper functioning of the system during simulated prelaunch operations, including rotation to the launch attitude, behavior during VMA cutoff and during repumping.

9. Verify sealing of V7 and isolation of the cold fill line, and the sealing of V5 and V17.

10. Measure the performance of the DSS in the upright attitude with (a) LHe and (b) SHe.

11. Measure the performance of the DSS in the tilted attitude with SHe.

12. Measure the performance of the DSS with SHe and with the vent flow divided to simulate cooling of the cryostat.

13. Measure the performance of the DSS with SHe and with simulated pumping by the vacuum maintenance assembly (VMA), including repumping after pump cutoff.

14. Measure the rates of SHe warming without pumping.

15. Measure the gas pumping capability of the porous plug.

16. Measure the performance of the porous plug in controlling SHe.

17. Determine the effects of SHe film wetting of the porous plug.

18. Determine the effects of operating the porous plug heater H3.

TABLE 3. SUMMARY OF TPE OBJECTIVE ACCOMPLISHMENTS

TEST OBJECTIVE				TPE NUMBER								
OBJECTIVE #	DESCRIPTION	ORIENTATION	LIQUID STATE	I	II	III	IV	V	VI	VII	TEST COMPLETED	OBJECTIVE #
1a	Verify Safe	Up	N	X	X	X	X	X	X	X	X	1a
1b	Verify Safe	Up	S	(X)	X		X	X	X	X	X	1b
2	Verify Safe	Tilt	S					X	X	X	X	2
3	Verify Inst. Syst.			X	X		X	X	X	X	X	3
4a	Verify Fill	Up	N	X	X	X	X	X	X		X	4a
4b	Verify Topoff	Up	N					X	X		X	4b
5	Verify Conversion	Up	N→S	X	X		X	X	X	X	X	5
6a	Verify Fill	Up	L									6a
6b	Verify Topoff	Up	L									6b
7a	Verify Fill	Tilt	L									7a
7b	Verify Topoff	Tilt	L									7b
8	Verify Prelaunch	Tilt	N,L,S						(X)	(X)	(X)	8
9	Verify Valves						X	X	X	X	X	9
10a	Measure Performance	Up	N	X							X	10a
10b	Measure Performance	Up	S		X		X				X	10b
11	Measure Performance	Tilt	S					(X)	X	X	X	11
12	Measure Divided Flow		S		(X)		(X)		X		X	12
13	Verify VMA Sim.	Tilt	S		X				X	X	X	13
14	Measure Warming		S		X				X	X	X	14
15	Measure Plug-Gas		S		(X)		(X)	X		X	X	15
16	Measure Plug Perf.	Tilt	S					X		X	X	16
17	Measure Film Flow	Tilt	S					X	X	X	X	17
18	Measure Heater	Tilt	S					X		X	X	18

N = Normal Liquid
S = Superfluid
L = Low Pressure Liquid (not superfluid)
(X)= Partially Completed

TABLE 4. INDEX OF MAJOR EVENTS, TPE I

EVENT	TIME(S)	ACTIVITY	REMARKS
A	11:06:0900-11:06:1500	First Cooldown and LHe transfer attempt	No liquid collected.
B	11:06:1500-11:10:1230	Warmup	
C	11:10:1230-11:10:1500	Second cooldown and LHe transfer attempt	No liquid collected.
D	11:10:1500-11:16:1210	Warmup	
E	11:16:1210-11:16:1700	Third Cooldown and LHe transfer attempt	No liquid collected.
F	11:16:1700-11:17:1450	Warmup	
G	11:17:1450-11:17:1600	LHe transfer	Collected 147 liters. Lab. transfer line.
H	11:17:1600-12:01:1030	LHe stabilization and performance	
I	12:01:1040-12:01:1616	First conversion to SHe	T_λ at 1308.
J	12:01:1616	Blockage of vent line	22.5ℓ SHe remains.
K	12:01:2240	Blockage open	T2 = 55K T3 = 89K T4 = 156K
L	12:03:0420	Last LHe evaporates	
M	12:03 -12:22	Warmup	Install and check leak fixes.

TABLE 5. INDEX OF MAJOR EVENTS, TPE II

EVENT	TIME(S)	ACTIVITY	REMARKS
A	12:23:0900-12:23:1430	Cooldown and LHe transfer	Collected 241 liters.
B	12:23:1430-12:28:1310	LHe stabilization	Thermoacoustic oscillations. High boiloff rate.
B'	12:24:1010	Depressurize dewar	920 torr to 753 torr, abs.
C	12:28:1310-12:29:1400	Conversion to SHe	T_λ at 12:28:1700 T1 min = 1.619K at 29:1400
D	12:29:1400-01:15:1200	SHe steady state test	
D'	01:13:1700	Bay doors open spontaneously	Room cooled for ∿ 14 hrs.
E	01:15:1200	Last SHe evaporates	
F	01:15:1200-01:18:1040	Partial warmup	
G	01:18:1040-01:18:1340	LHe refill	Dewar empty, cold. Collected 243ℓ. Used 360ℓ.
H	01:18:1340-01:19:0940	LHe stabilization	TAO's evident.
I	01:19:0940-01:20:1000	Conversion to SHe	T_λ at 1425
J	01:20:1000-01:20:1305	SHe warmup test	No pumping. 126ℓ warms, 1.678K to 1.815K. See Figure 9.
K	01:20:1305-01:21:1000	Dewar repump test	S16 pump
L	01:21:1000-01:22:0700	Porous plug gas flow test	Close V5 lightly. T5 and T6 cooled. See Fig. 10.
M	01:22:0700	Plug flow partially blocked, SHe warms.	LL probe heated for few sec. T5 and T6 warm abruptly. See Fig. 9.
N	01:22:0800-01:23:1515	Repump	Open V5; later connect S60 pump.
P	01:23:1515-01:28:0815	Divided flow test	F2 through small diam. line.
P'	01:24:0955	Reduce F1	
P"	01:25:1400-01:25:1600	Change fill line	Pressurize, then repump. F2 through large diam. line.
Q	01:28:0815-01:29:0000	Pressurize dewar	Move DSS into flight support structure.
R	01:29:0000-02:03:1330	LHe steady state test	
S	02:03:1330	Last LHe evaporates	
T	02:03:1330-02:11:0855	Partial warmup	To TPE III.

TABLE 6. INDEX OF MAJOR EVENTS, TPE III

EVENT	TIME(S)	ACTIVITY	REMARKS
A	2:11:0900-2:11:1430	Cooldown and LHe transfer	Collected 182 liters.
B	2:11:1430-2:11:1700	LHe stabilization	High boiloff rate. Relief valves on fill and vent. $P_{fill\ relief} < P_{vent\ relief}$
C	2:11:1700-2:11-2330	LHe blows out thru fill line	
D	2:11:2330	Last LHe gone	
E	2:11:2330-2:12:0730	Shields warming	
F	2:12:0730-2:12:0900	GHe purge to hasten warmup	
G	2:12:0900-2:22:0800	Shields warm without purge	

TABLE 7. INDEX OF MAJOR EVENTS, TPE IV

EVENT	TIME(S)	ACTIVITY	REMARKS
A	02:22:0820-02:22-1150	Cooldown and LHe transfer	Collected > 243 liters.
B	02:22:1235-02:23:0730	Conversion to SHe	T_λ at 1830
C	02:23:0730-03:01:0810	Divided flow test	F2 10 mg/s
C'	02:24:0820	Adjust F1 and F2	
C"	02:24:1500	Adjust F2	To ∿ 10 mg/s
C"'	02:26:1610	Adjust F1	To ∿ 5 mg/s
C""	02:27:1730	Adjust F2	To ∿ 10 mg/s
D	03:01:0810-03:04:1700	SHe stabilization	F1 only
D'	03:02:0930	Adjust F1	To ∿ 8.5 mg/s
D"	03:02:1200	Adjust F1	To keep T1 < T_λ
D"'	03:03:1048-03:03:1231	Porous plug gas flow test	> T_λ at 1159
D""	03:03:1515-03:03:1615	SHe warmup test Cold valve closure test	6ℓ warms, 2.042K to 2.226K > T_λ at 1545
E	03:04:1700-03:09:1300	Partial warmup	To TPE V

TABLE 8. INDEX OF MAJOR EVENTS, TPE V

EVENT	TIME(S)	ACTIVITY	REMARKS
A	03:09:1300-03:09:1554	Cooldown and LHe Transfer	Collected 243 liters.
B	03:10:0700-03:10:0800	LHe Topoff	Added 41 liters.
C	03:10:0810-03:11:1240	Conversion to SHe	T_λ at 10:1230.
D	03:11:1240-03:11:1350	Porous plug gas flow test	
E	03:12:1300-03:13:0010	First tilt test	See Figure 21.
F	03:13:1626-03:13:1805	Second tilt test	See Figure 26.
G	03:14:0820-03:14:0924	Third tilt test	See Figure 26.
H	03:15:0800-03:15:1626	Fourth tilt test	See Figure 27.
I	03:16:0811-03:16:1715	Fifth tilt test	See Figure 33.
J	03:16:1715-03:21:1230	SHe steady state test	Confirms high heat load.
K	03:21:1230	Last SHe evaporates	
L	03:21 -03:30	Warmup	With active purge. To acoustic test.

TABLE 9. PLUG HEATER TEST DATA

	T1 (K)	T5 (K)	T6 (K)	F1 (mg/s)	Current (mA)	Voltage (V)	Power (mW)	Duration (sec)	Response
FIRST TEST									
Start	1.956	1.963	1.952	40.0					
Heater					1	6.0	6	1	
End	1.956	1.963	1.952	39.9					No Effect
SECOND TEST									
Start	1.955	1.963	1.952	39.9					
Heater					1	6.0	6	9	
End	1.955	1.963	1.952	39.8					No Effect
THIRD TEST									
Start	1.955	1.962	1.951	39.8					
Heater					3.16	19.1	60	10	
End	1.954	1.962	1.951	39.7					No Effect
FOURTH TEST									
Start	1.953	1.961	1.950	39.6					
Heater					3.16	19.1	60	30	
End	1.953	1.963	1.952	39.8					2 mK Warmup
FIFTH TEST									
Start	1.951	1.960	1.949	39.5					
Heater					10.0	60.0	600	30s	
End	1.951	1.968	1.957	40.5					8 mK Warmup 2.5% flow increase

TABLE 10. INDEX OF MAJOR EVENTS, TPE VI

EVENT	TIME(S)	ACTIVITY	REMARKS
A	07:13:0825-07:14:1320	Cooldown and LHe Transfer	
B	07:14:1320-07:15:0700	Conversion to SHe	T_λ at 1840.
C	07:15:0700-07:22:1130	SHe Steady State Test	
D	07:22:1130-07:22:1400	Porous Plug Gas Flow Test	Plug blocked.
E	07:22:1400-07:23:1415	Heat Plug with H3	Contaminants did not melt.
F	07:23:1415-07:25:0830	Repump SHe	
G	07:25:0830-07:30:1000	Divided flow test	
G'	07:25:0830-0930	Start F3, adjust F1	
G"	07:25:2210	Adjust F1	
G'''	07:27:2320	Adjust F1	
H	07:30:1000-08:05	Warmup and evacuate	Contaminants cleared from plug and lines.

TABLE 11. INDEX OF MAJOR EVENTS, TPE VII

EVENT	TIME	ACTIVITY	REMARKS
A	08:05:1730-08:05:2140	Cooldown and LHe Transfer	
B	08:05:2140-08:06:0715	Stabilization	
C	08:06:0715-08:06:1845	Conversion to SHe	T_{λ} at 1445
D	08:06:1845-08:09:1400	First Tilt Test	Inverted
E	08:07:0200-08:09:1400		System Oscillation
F	08:09:1400-08:12:0800	Second Tilt Test	Inverted
G	08:13:0800-08:15:2400	Stabilization	Dewar in Table
H	08:16:0000-	Warmup	

TABLE A1. SHe/LHe STORAGE COMPARISON; Q WATTS OF HEAT INTO 100 LITERS OF LIQUID

	Dewar Volume (liter)	Mass of Liquid (kg)	Total Energy to Evaporate (Joule)	Time Required to Evaporate (hour)	Mass Entering Vent Line (kg)	Mass Flow Rate (milligram/sec)	Heat Absorbed at 30 K at $\dot{m}$ (watt)
	V	$M = V\rho$	$U = LM$	$t = U/Q$	$M_V = .85\ M(LHe)$ $M_V = .99\ M(SHe)$	$\dot{m} = M_V/t$	$Q_a = \dot{m}\Delta H$
LHe	100	12.5	2.575×10^5	71.5/Q	10.6	41.2 Q	5.77 Q
SHe	100	14.5	3.335×10^5	92.6/Q	13.1	39.3 Q	5.74 Q
% Change		+16	+29.5	+29.5	+23.6	-4.8	-0.5

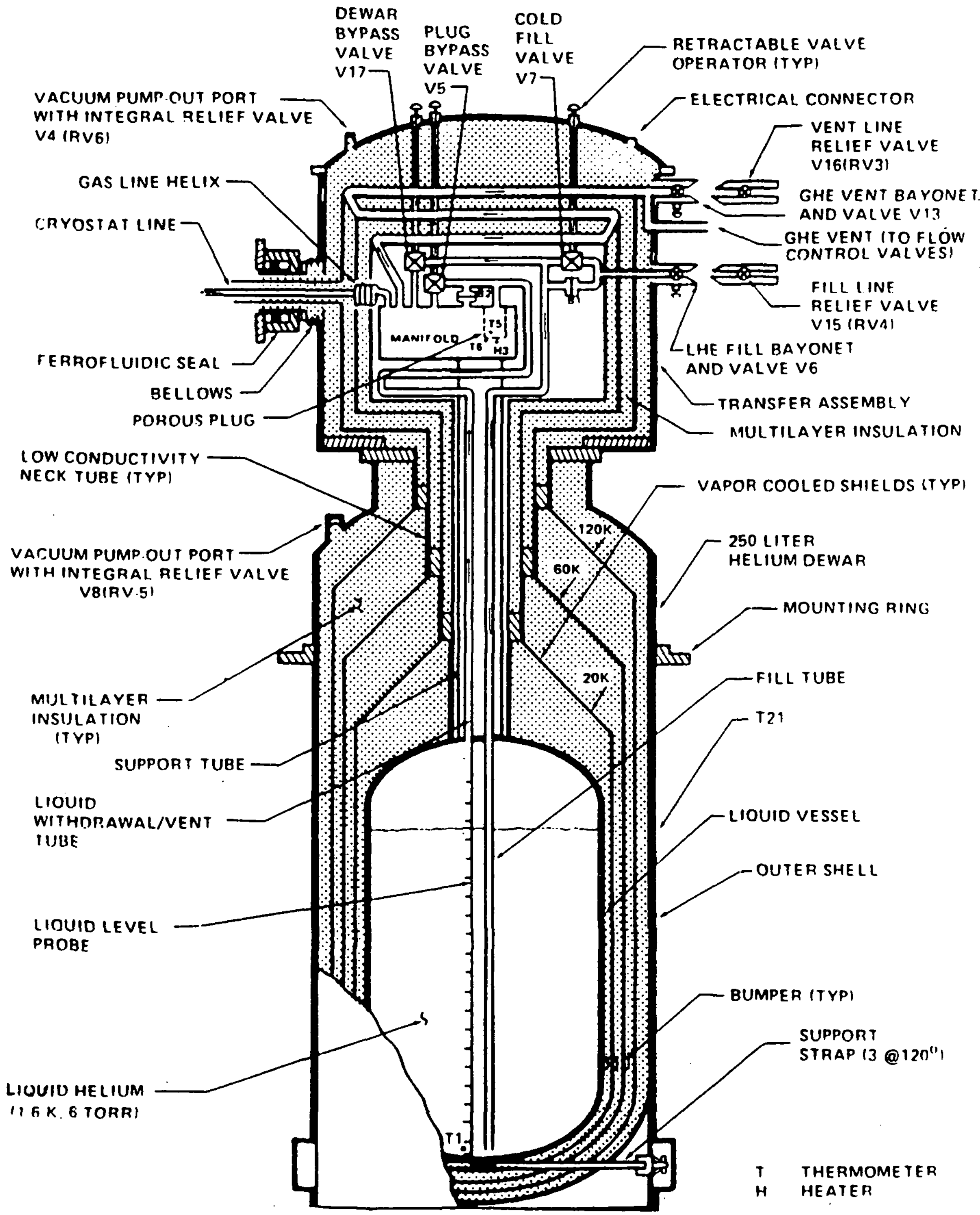

Figure 1. Schematic of IRT dewar subsystem, TPEs I-V.

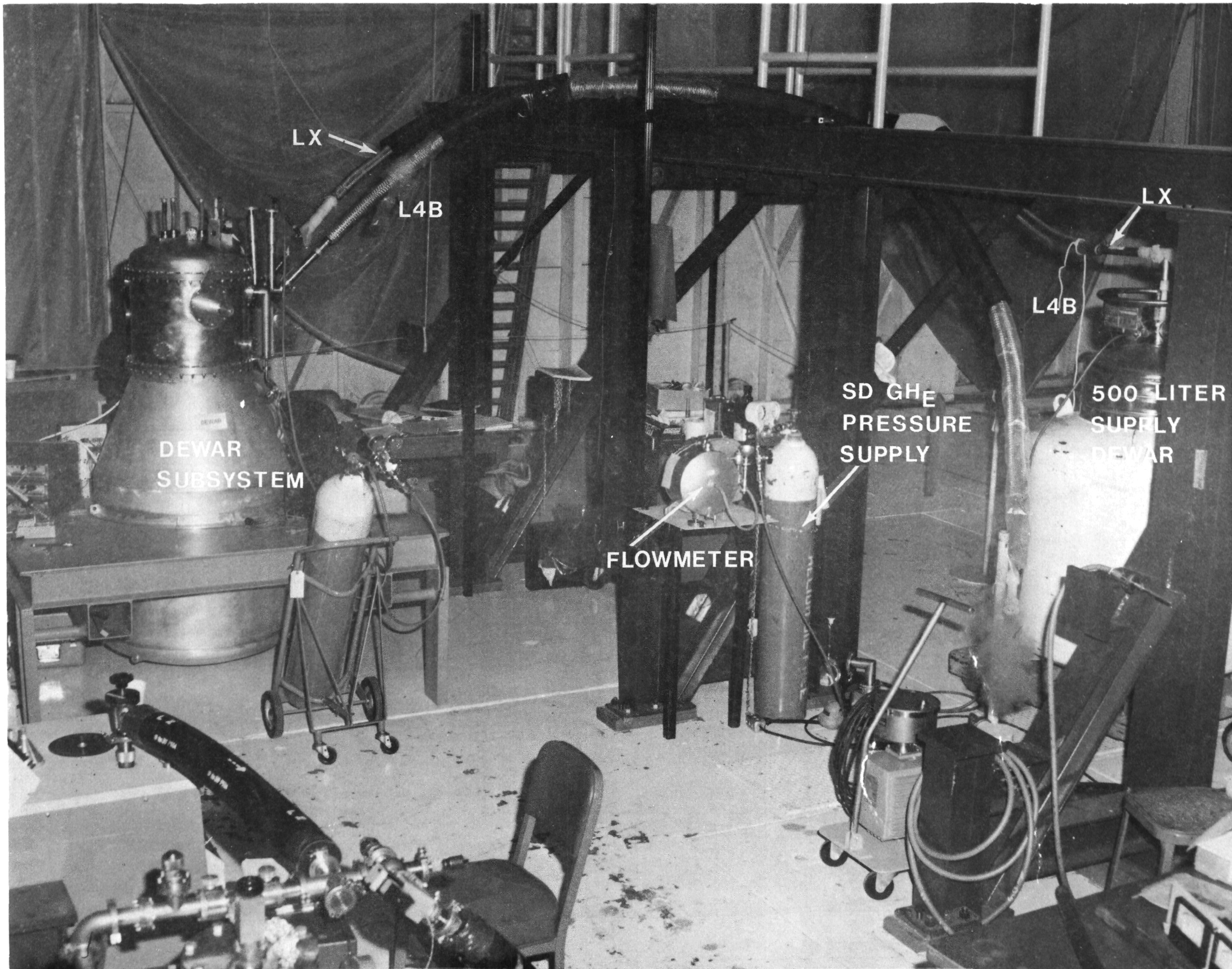

Figure 2. Dewar subsystem during initial filling, TPE I.

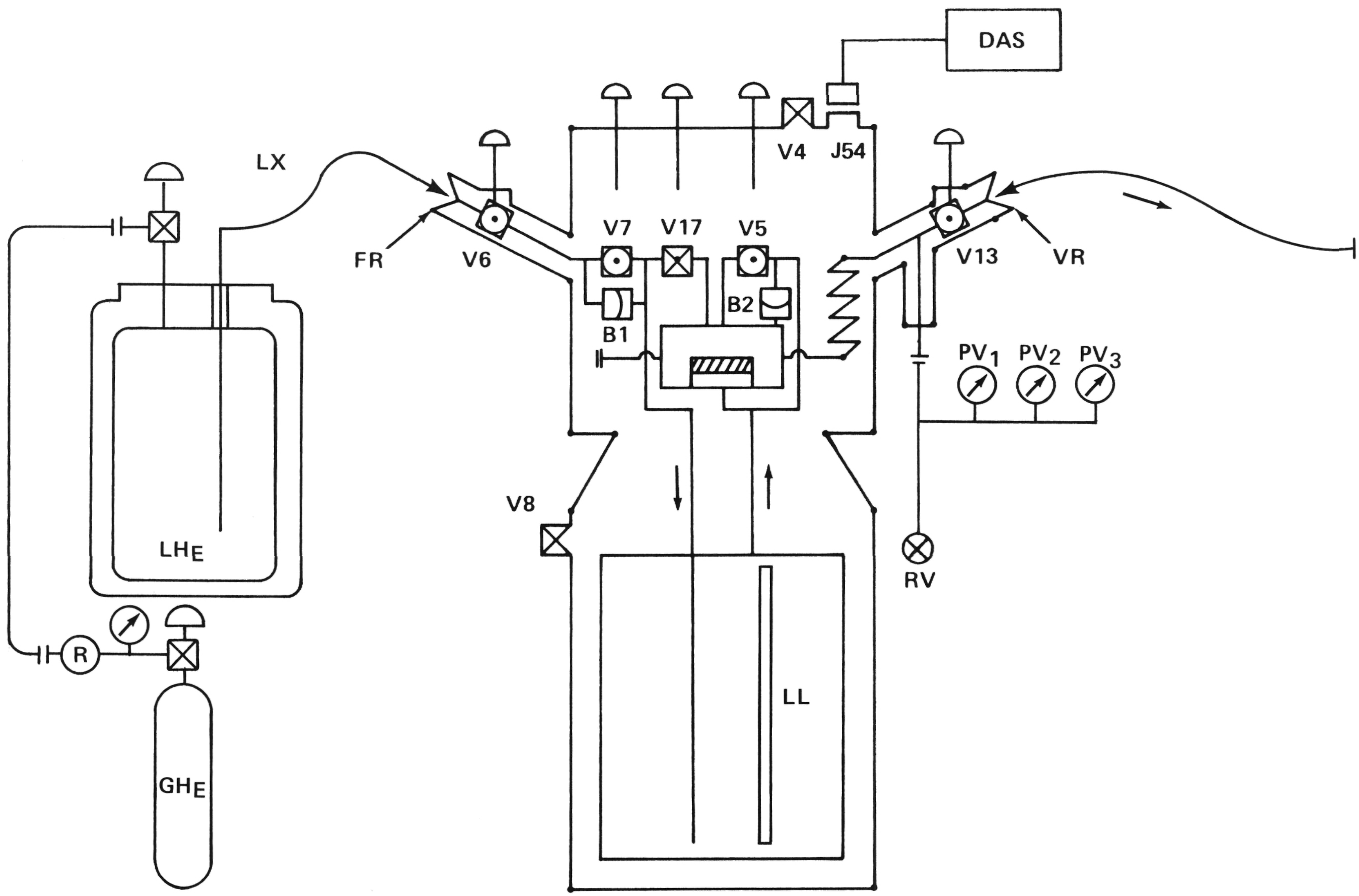

Figure 3. Schematic of DSS fill configuration, normal LHe, TPE I.

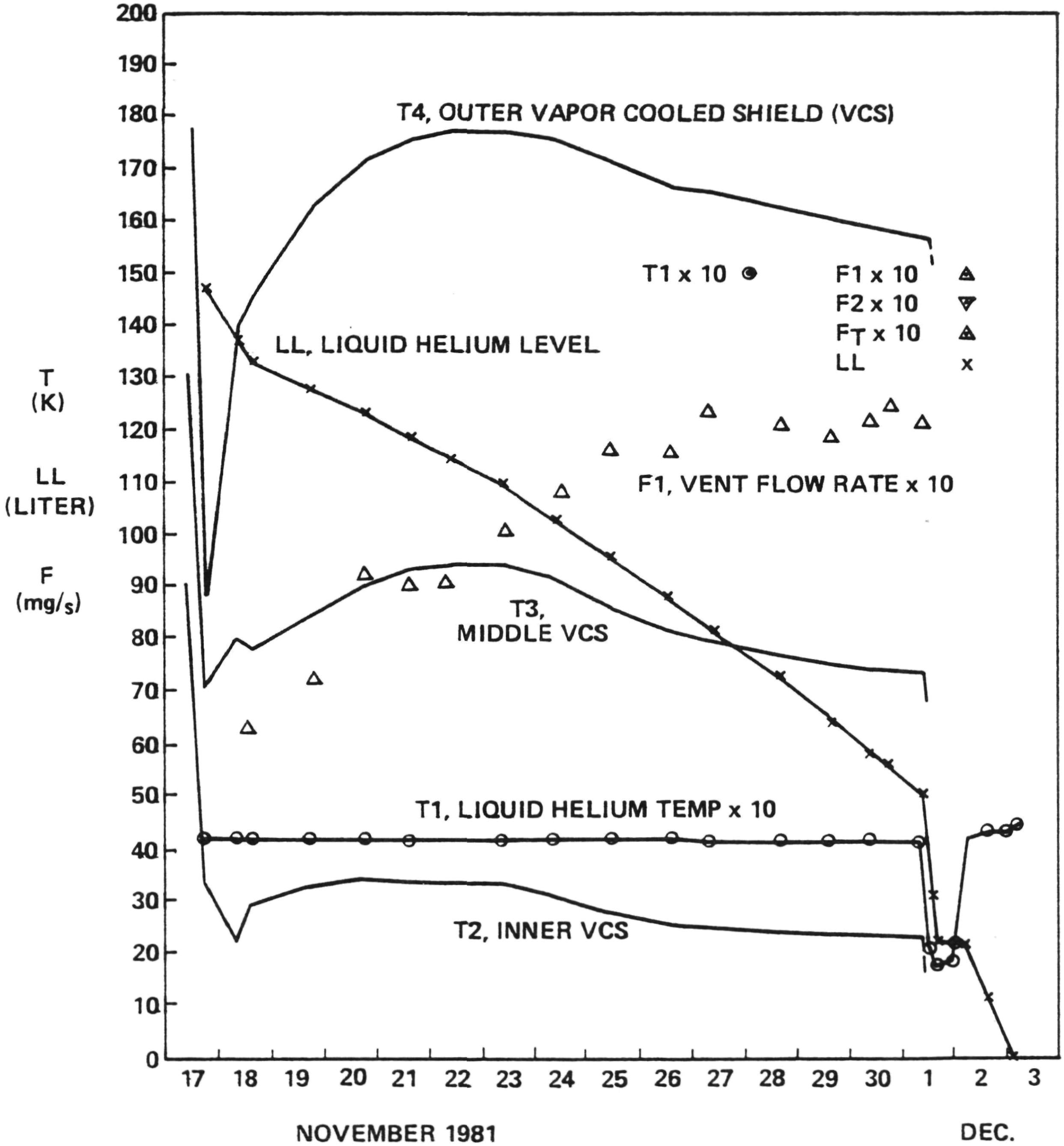

Figure 4. Graphical summary of TPE I.

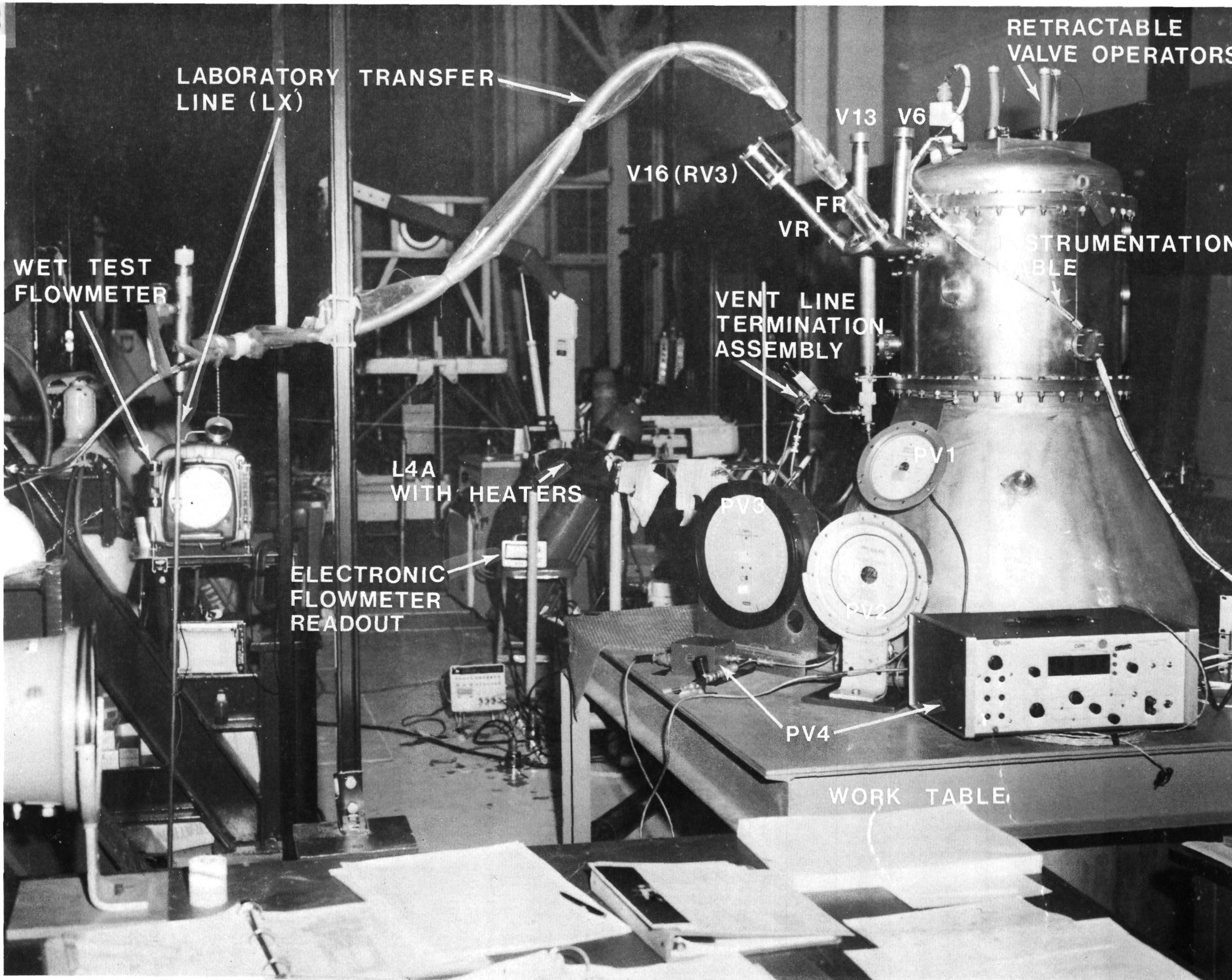

Figure 5. DSS with laboratory transfer line, TPE I.

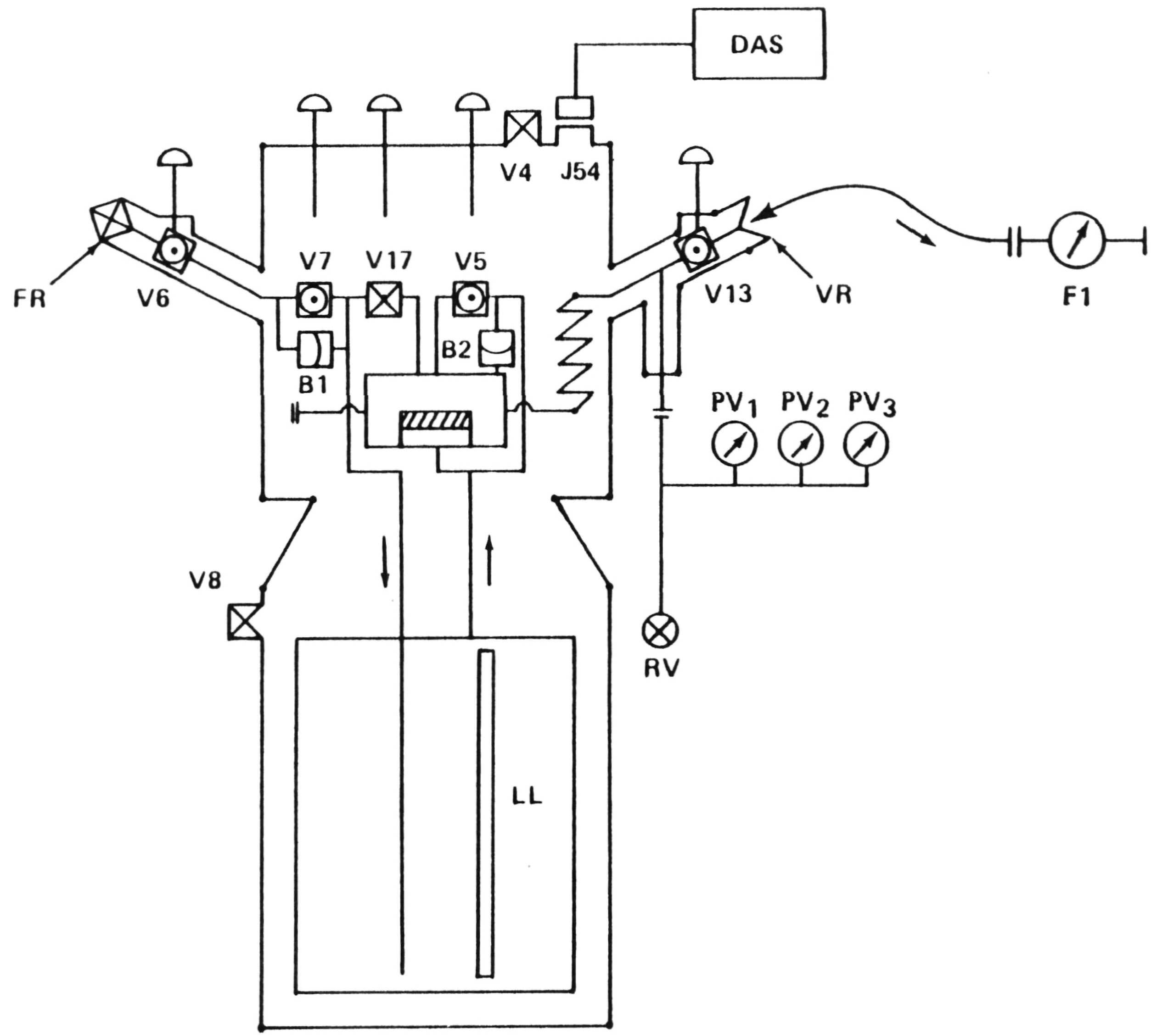

Figure 6. Schematic of TPE I test configuration.

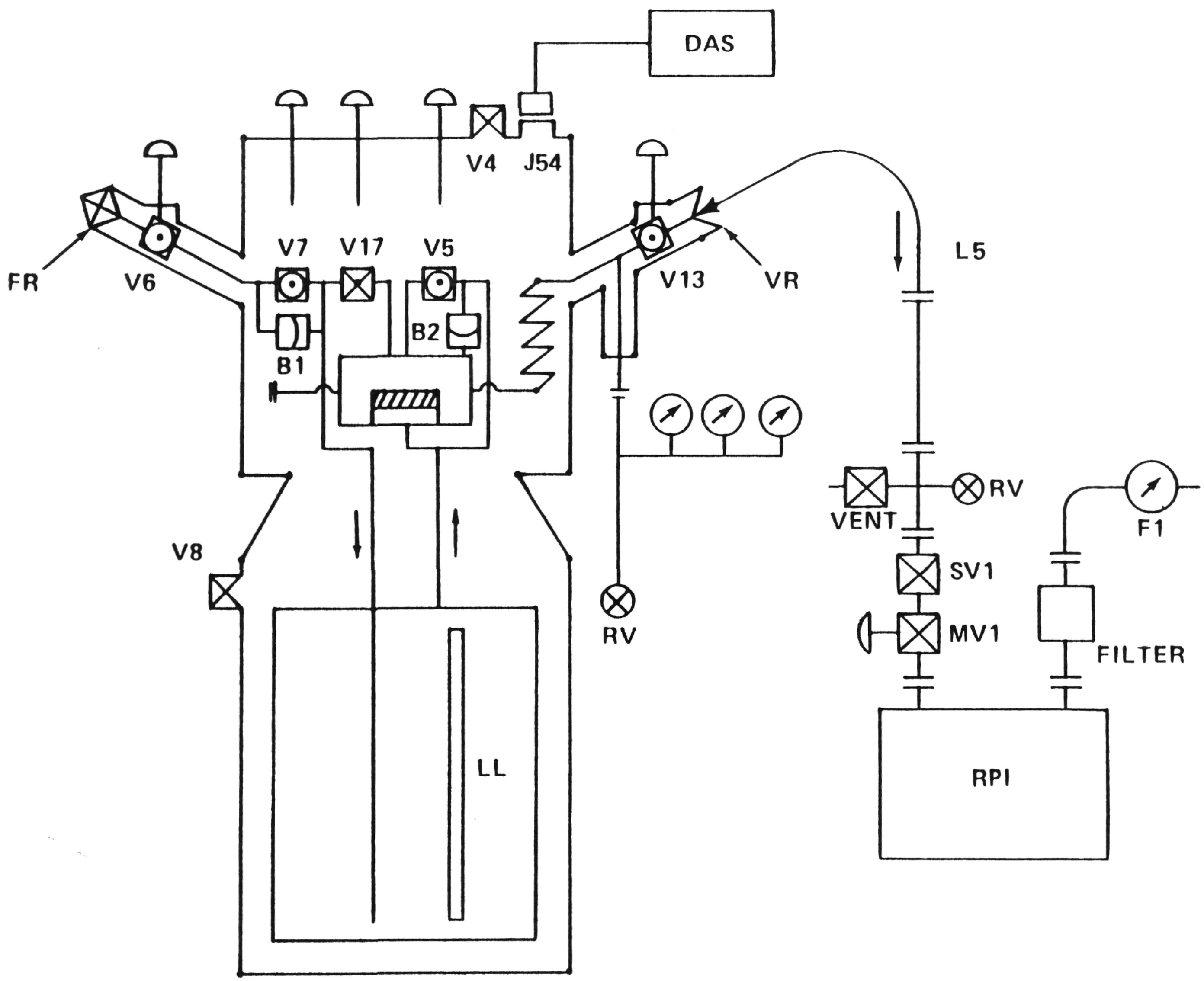

Figure 7. Schematic of TPE I configuration during SHe conversion.

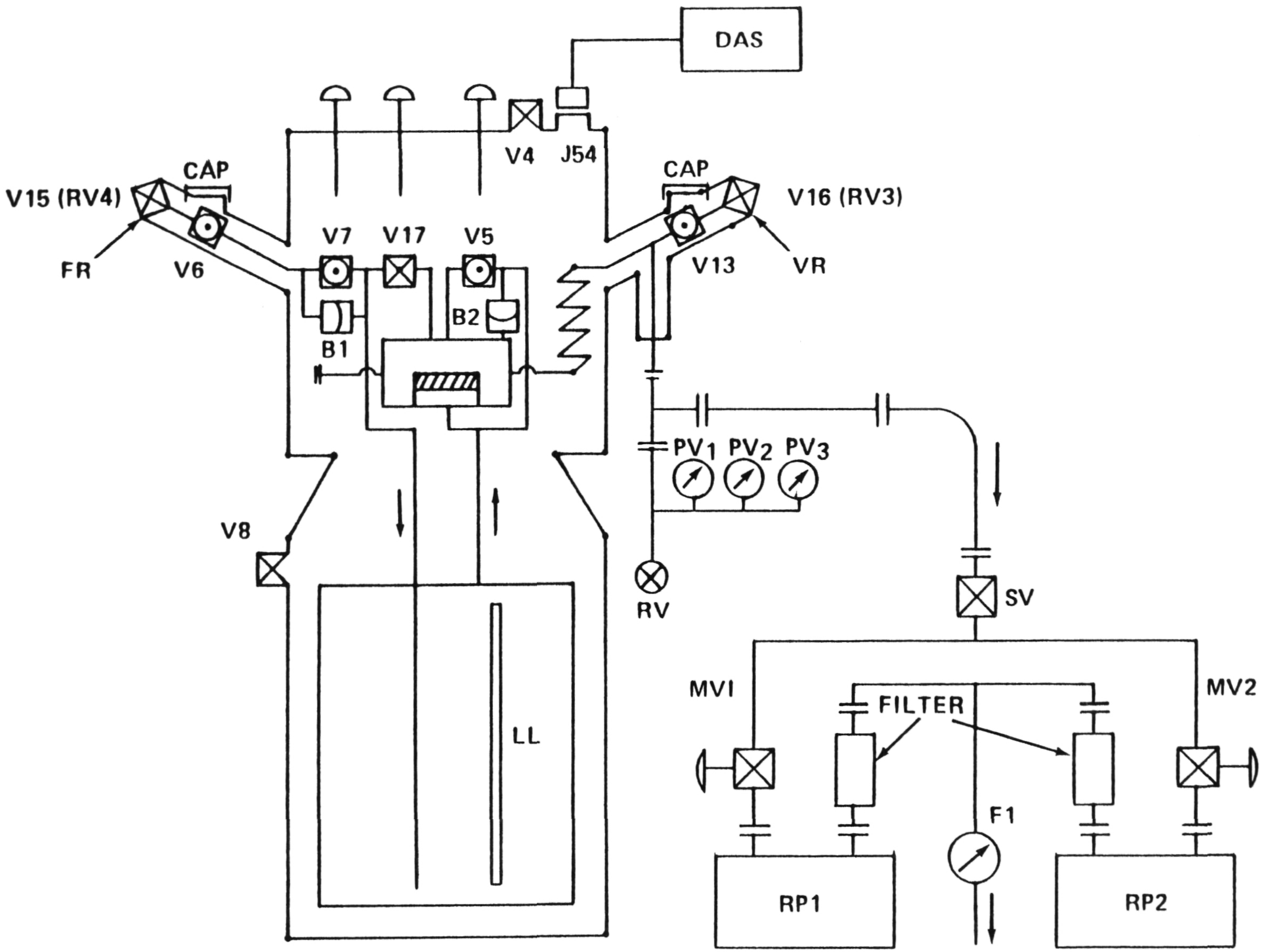

Figure 8. Schematic of TPE II configuration, first phase.

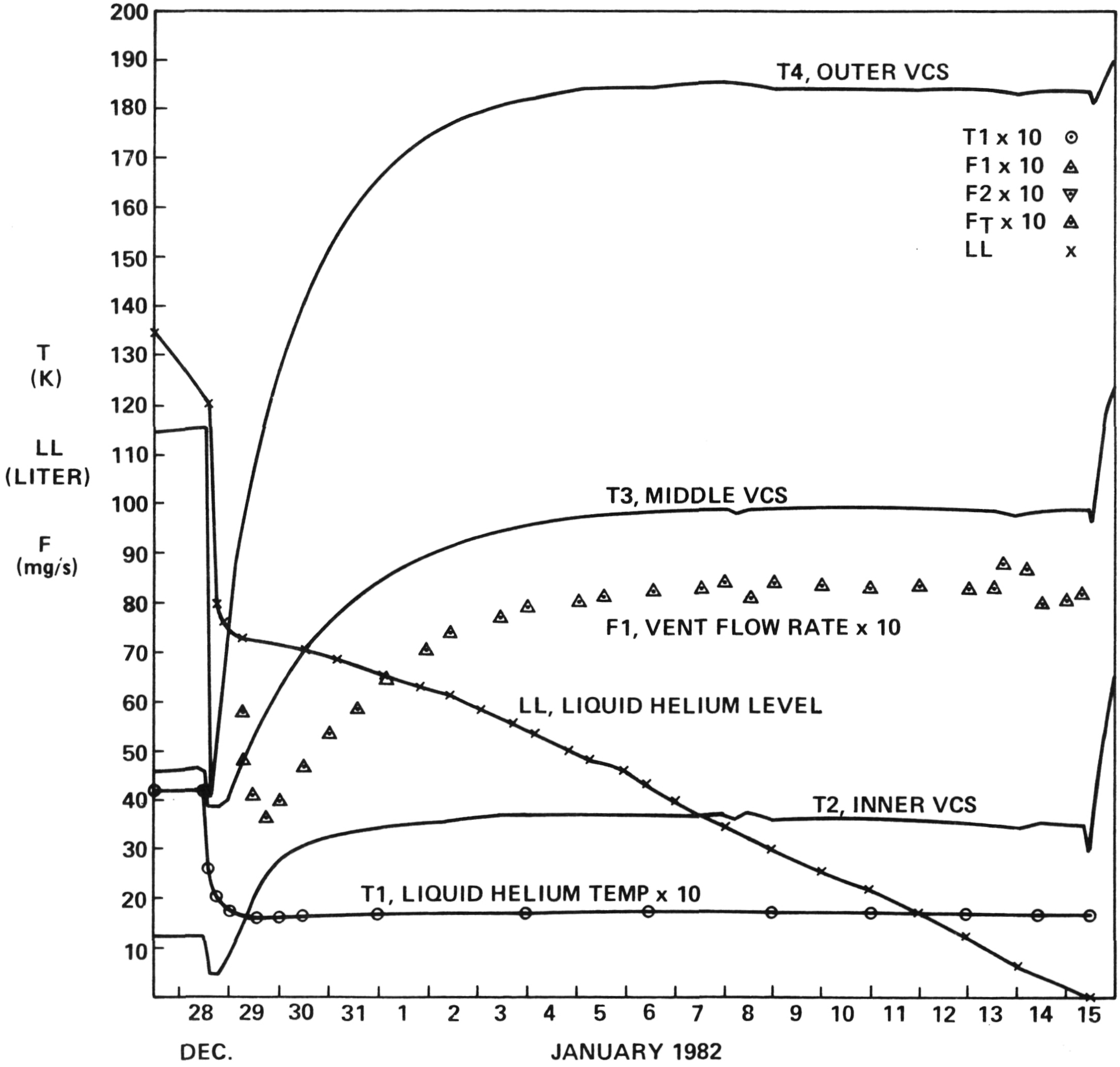

Figure 9. Graphical summary of TPE II, first phase.

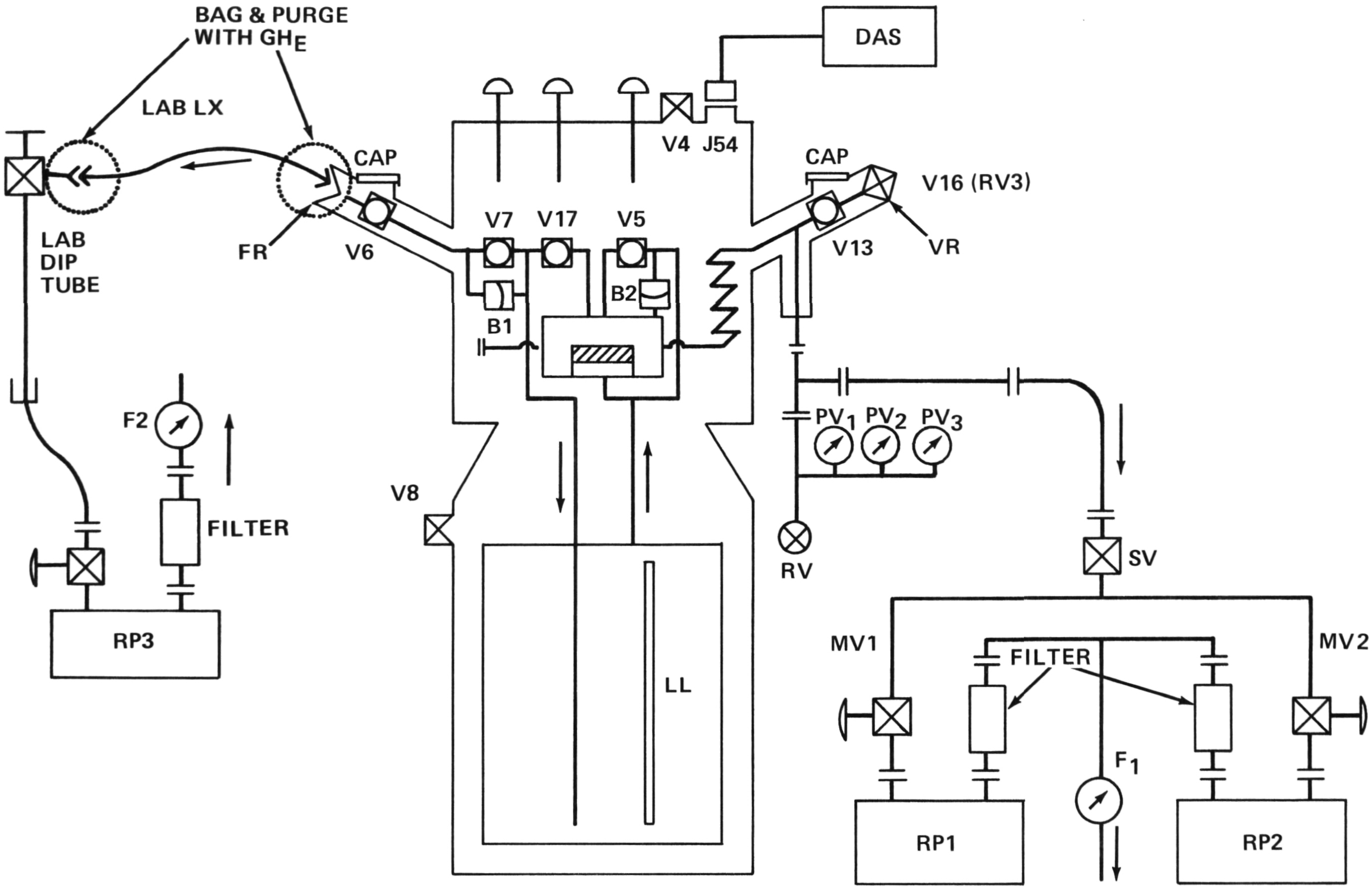

Figure 10. Schematic of TPE II test configuration, second phase.

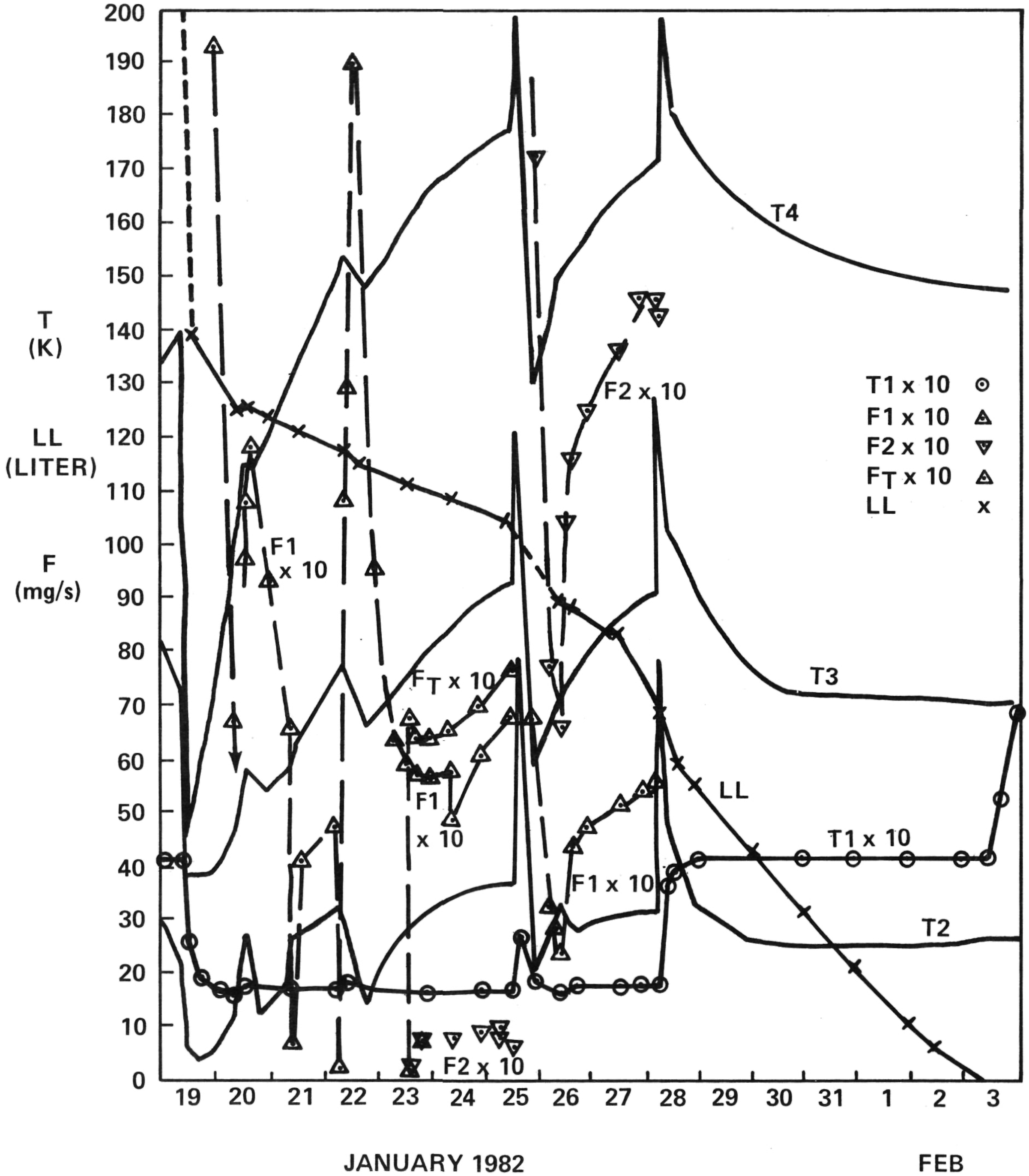

Figure 11. Graphical summary of TPE II, second phase.

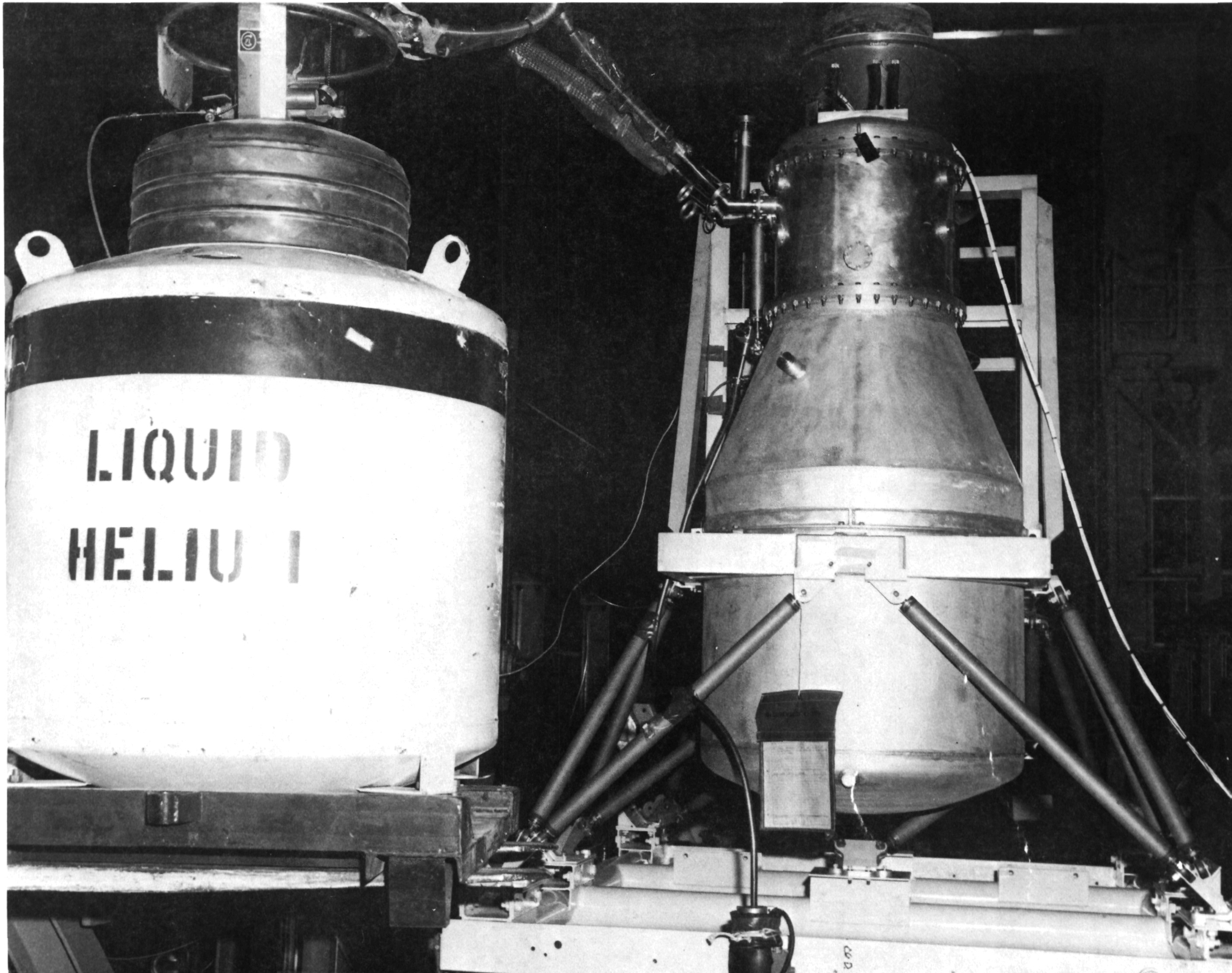

Figure 12, DSS in rotation support structure, TPEs III-IV.

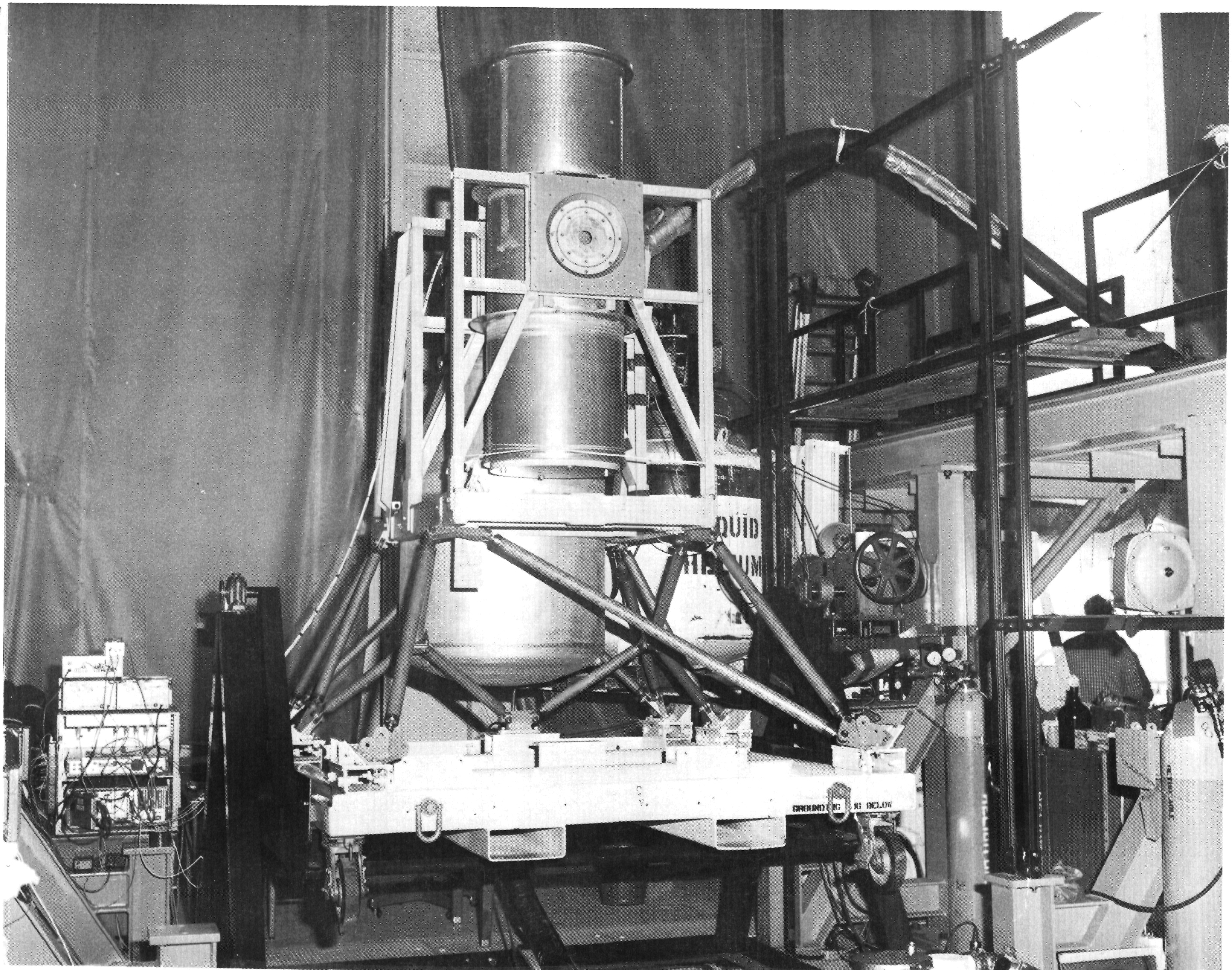

Figure 13. DSS in rotation support structure, TPEs III-IV.

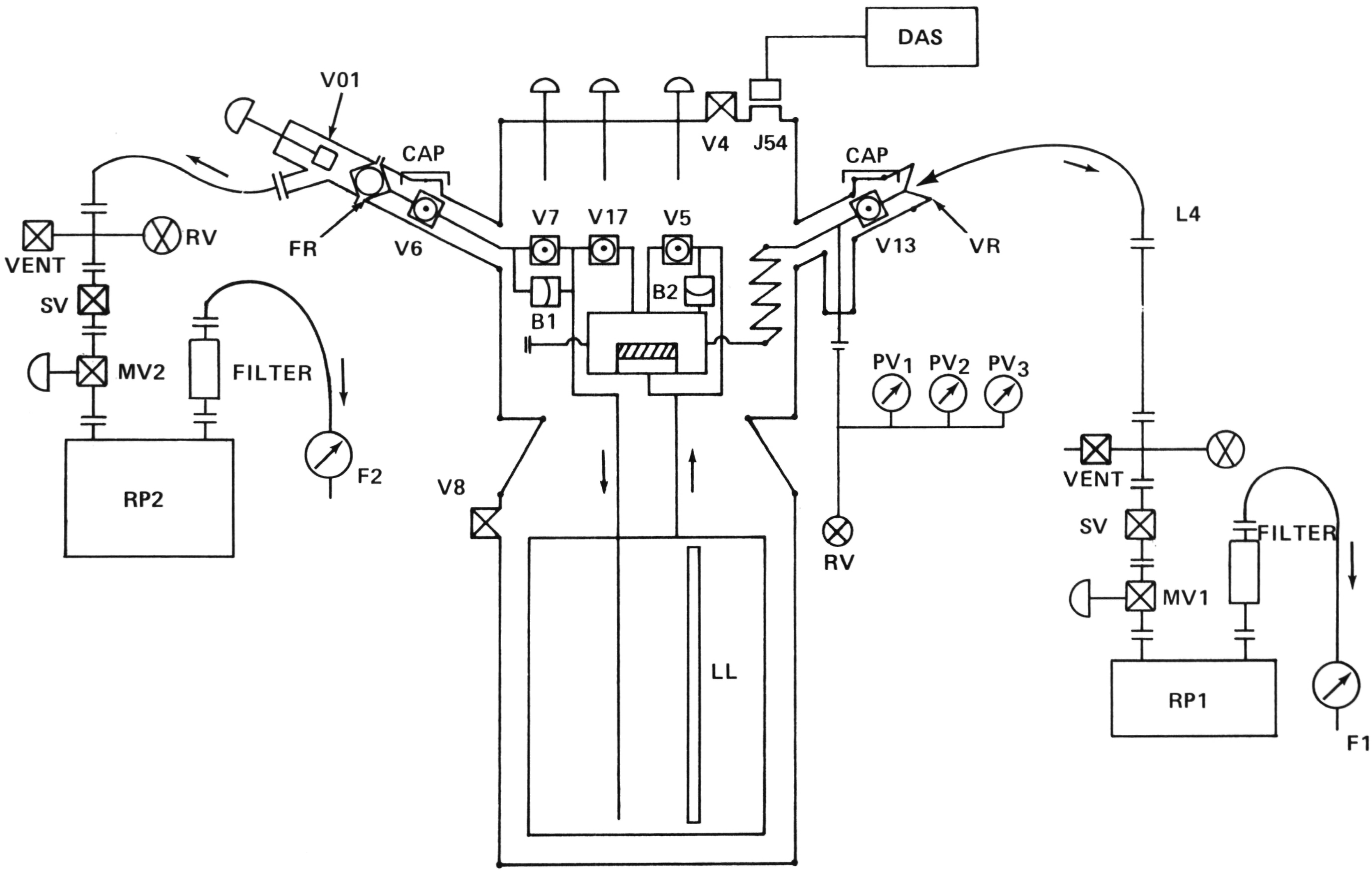

Figure 14. Schematic of test configuration, TPEs III-IV.

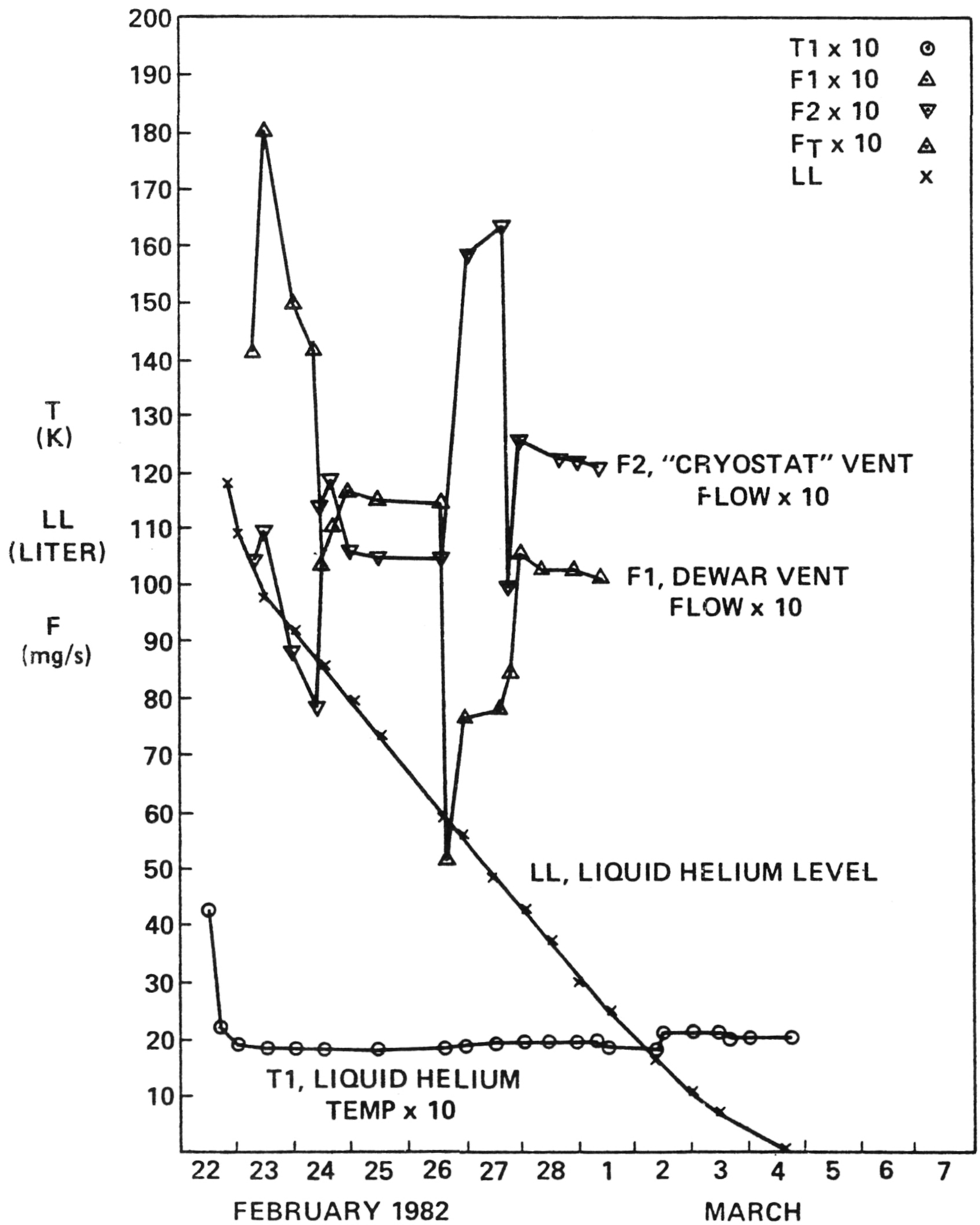

Figure 15. Graphical summary of TPE IV.

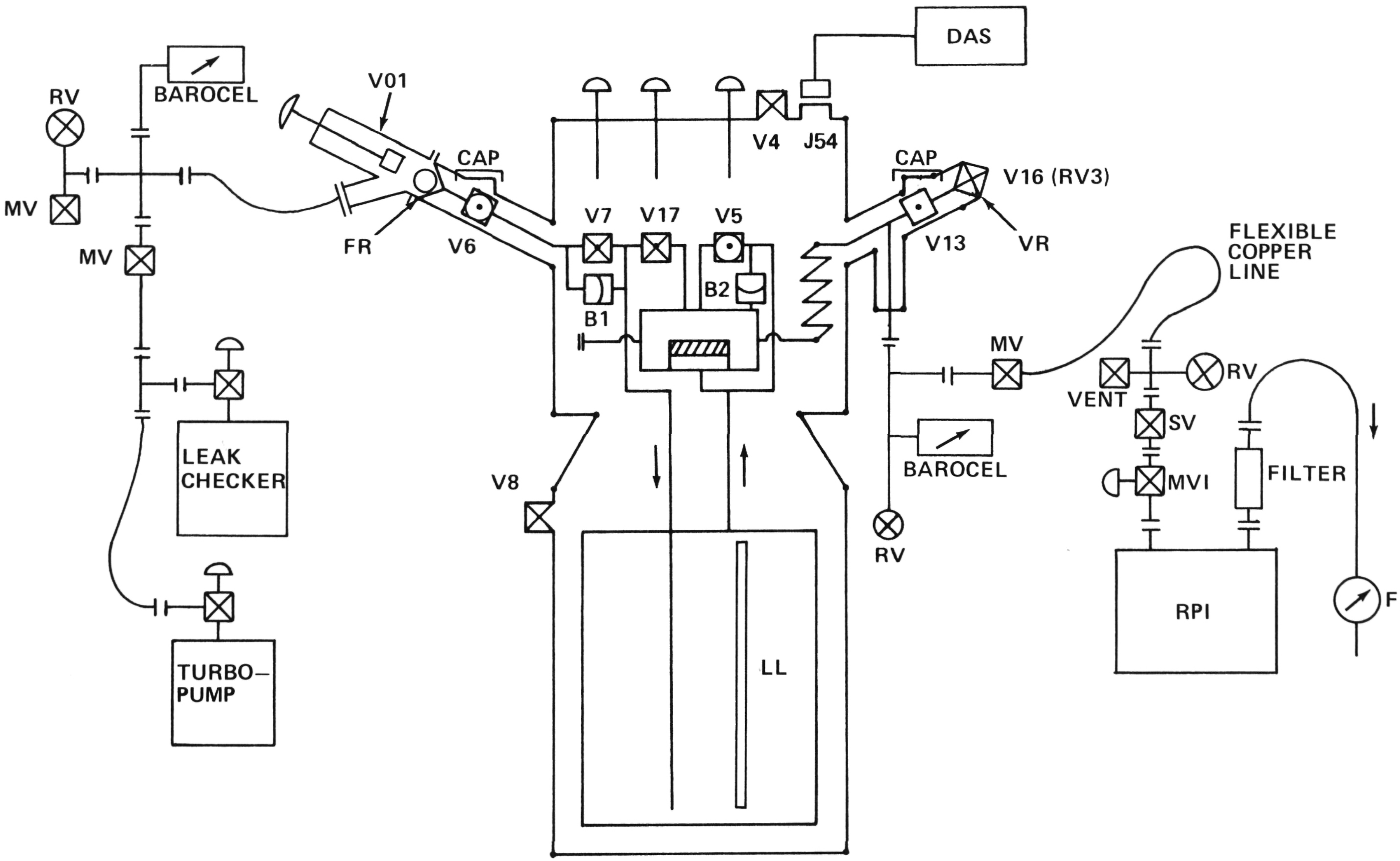

Figure 16. Schematic of TPE V test configuration.

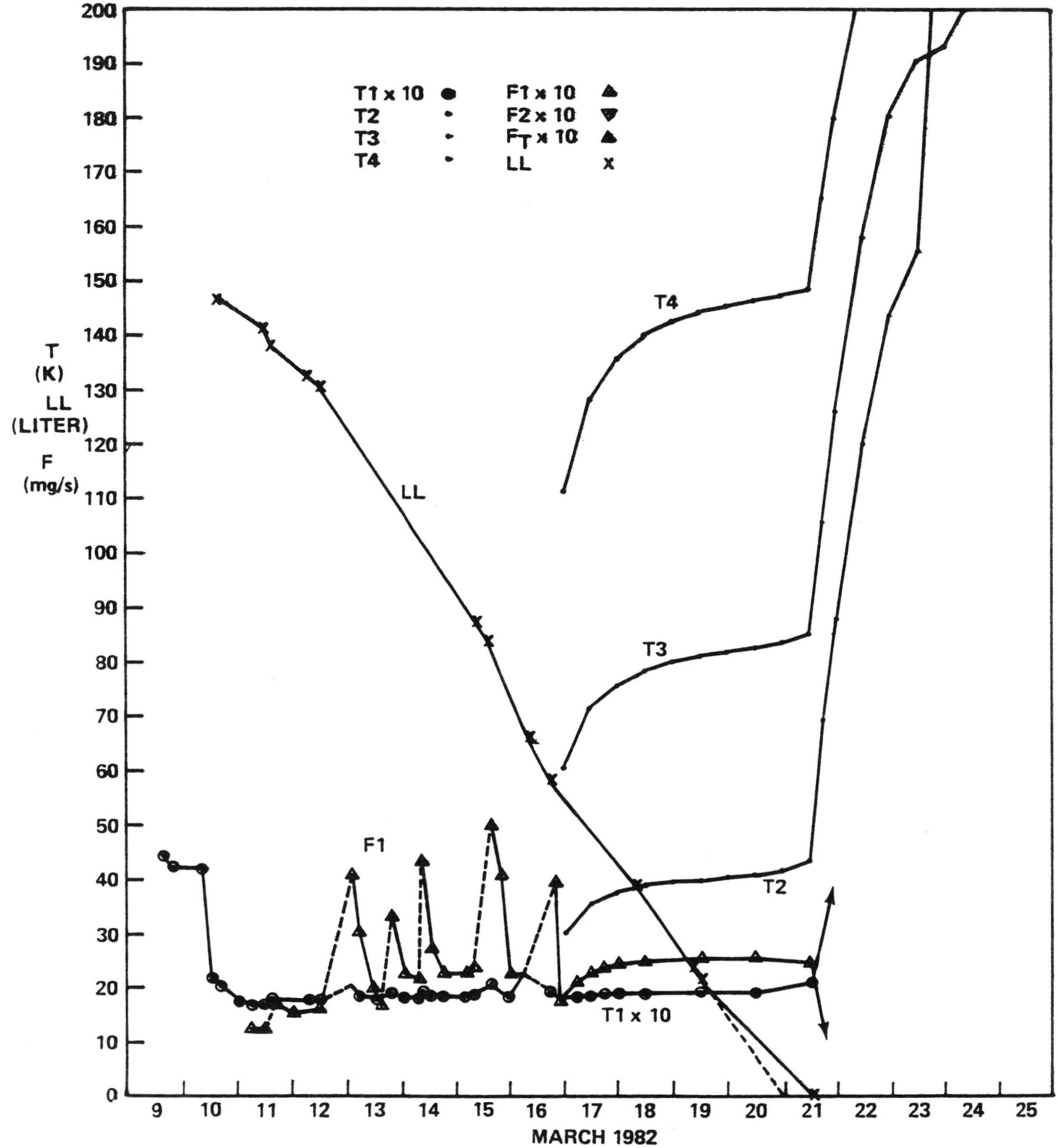

Figure 17. Graphical summary of TPE V.

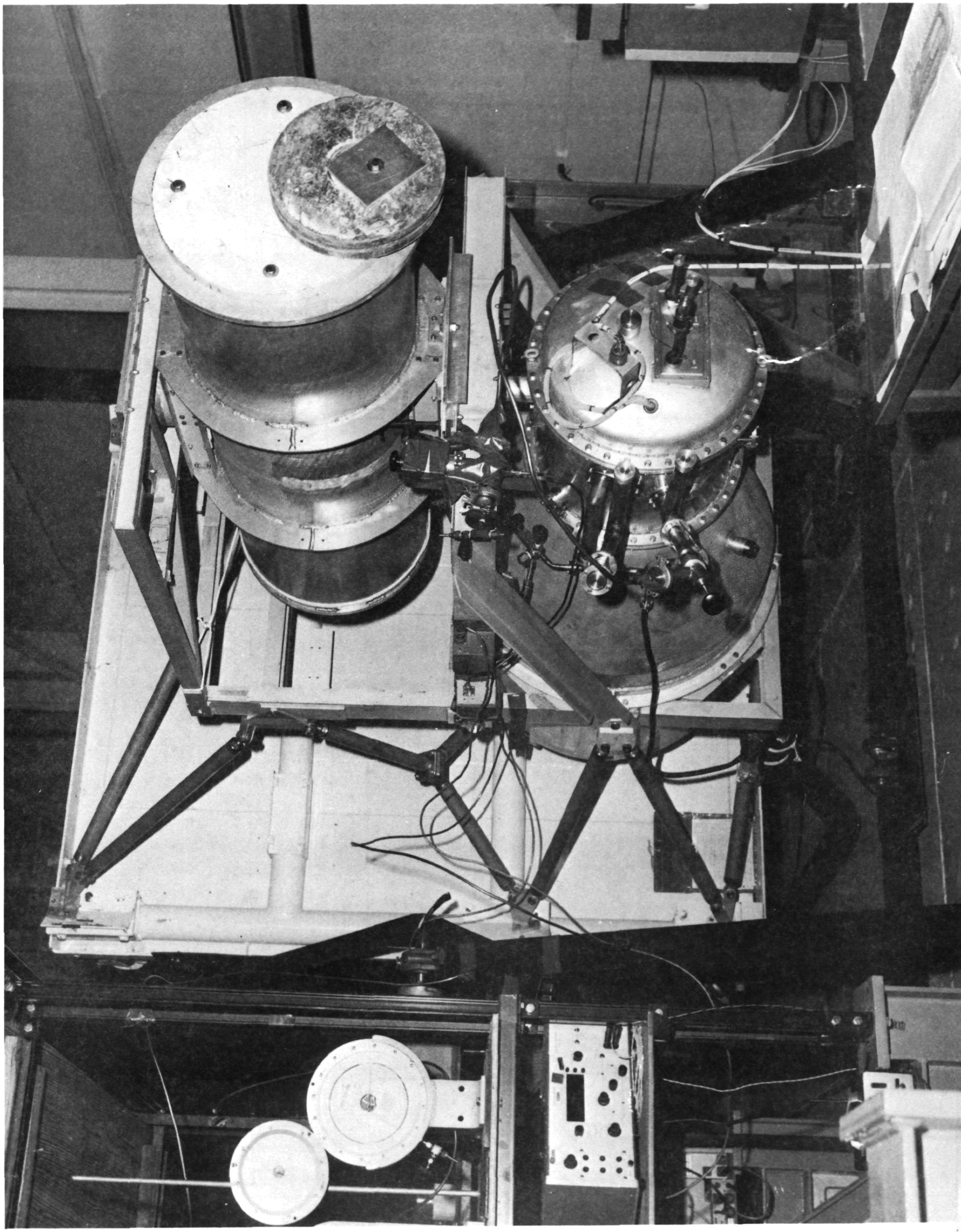

Figure 18. DSS during launch attitude tilt tests.

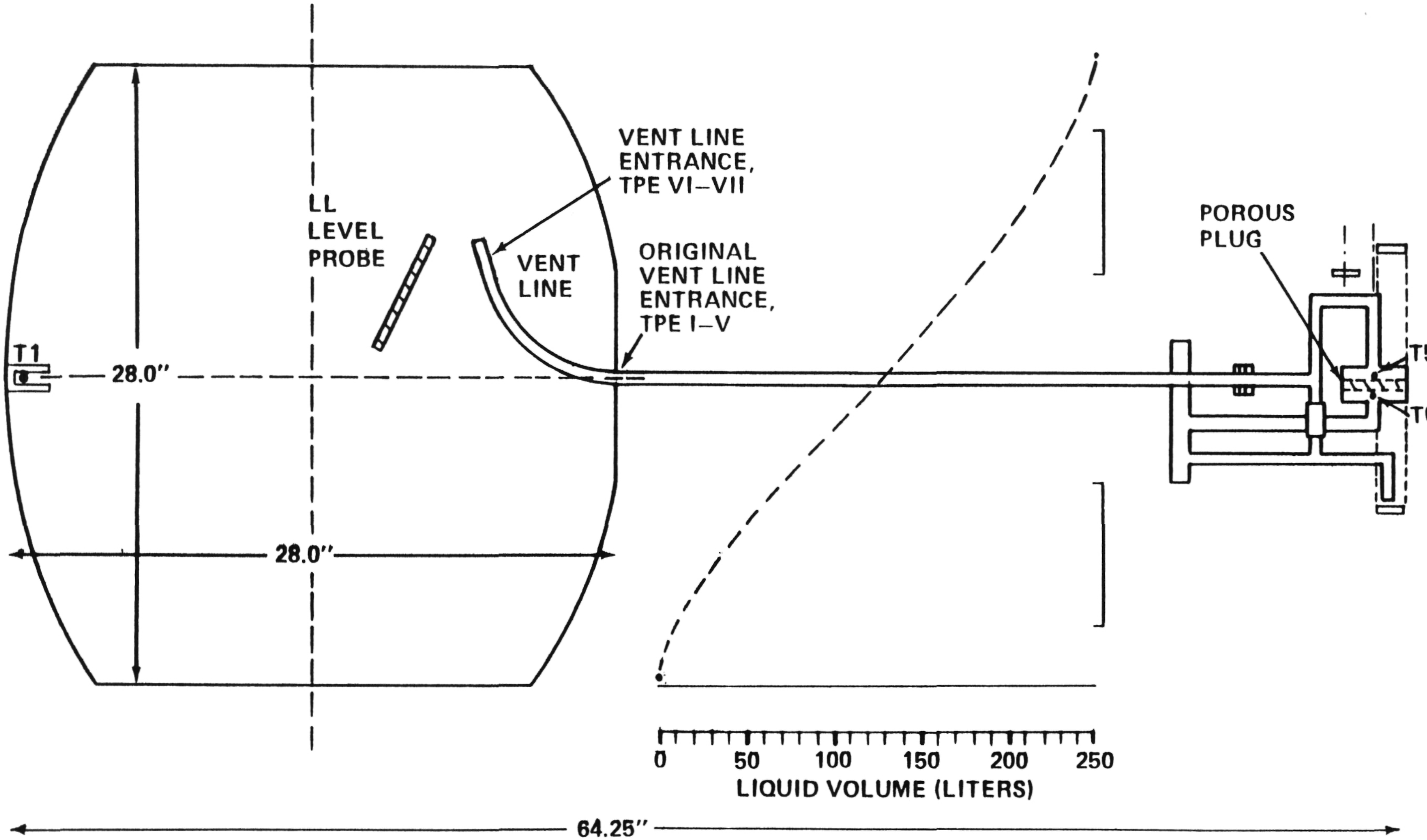

Figure 19. Scale drawing of dewar vessel, vent line, and porous plug with liquid volume curve.

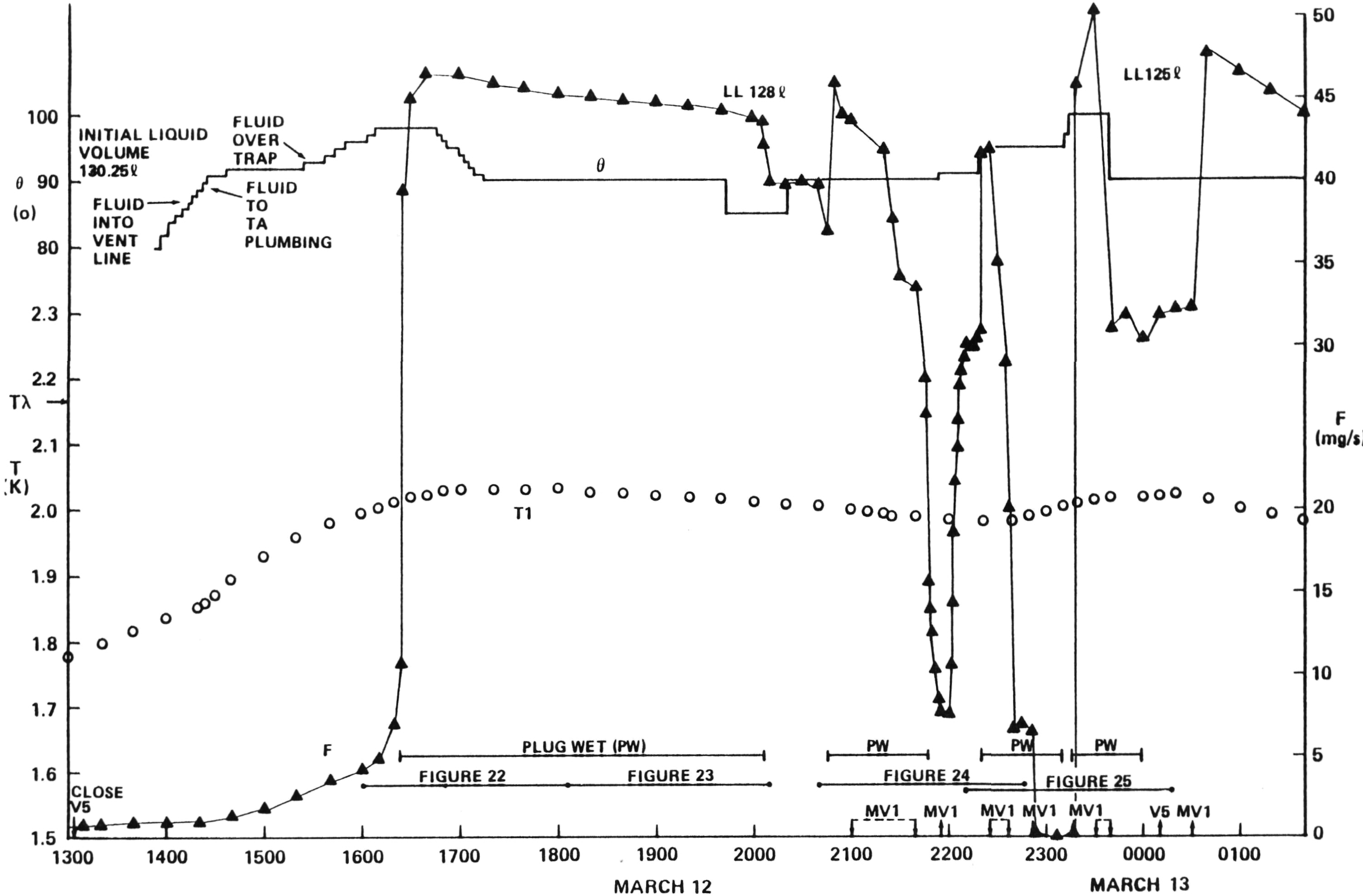

Figure 20. Graphical summary, first tilt test, TPE V.

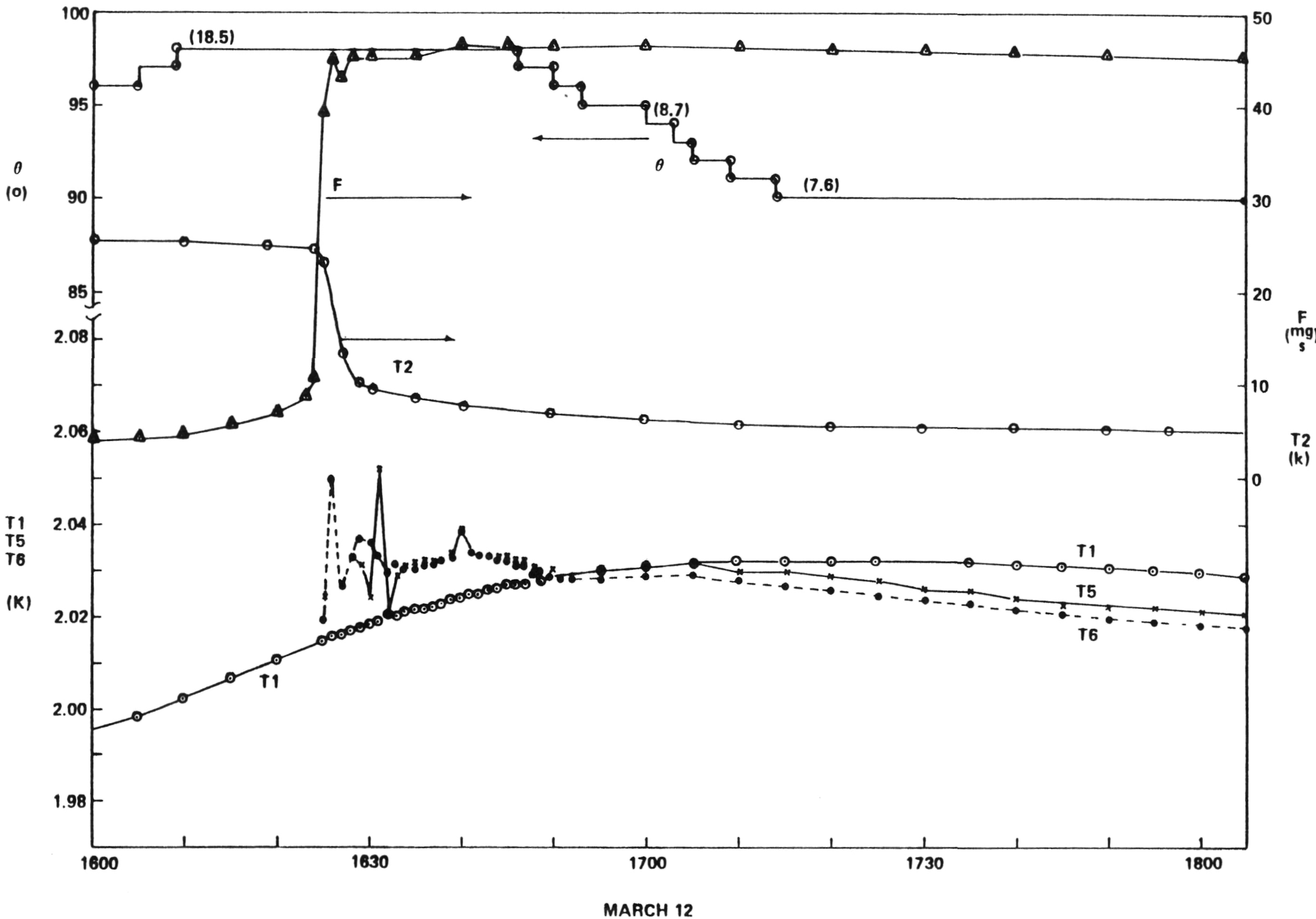

Figure 21. SHe on plug, first test, A, TPE V.

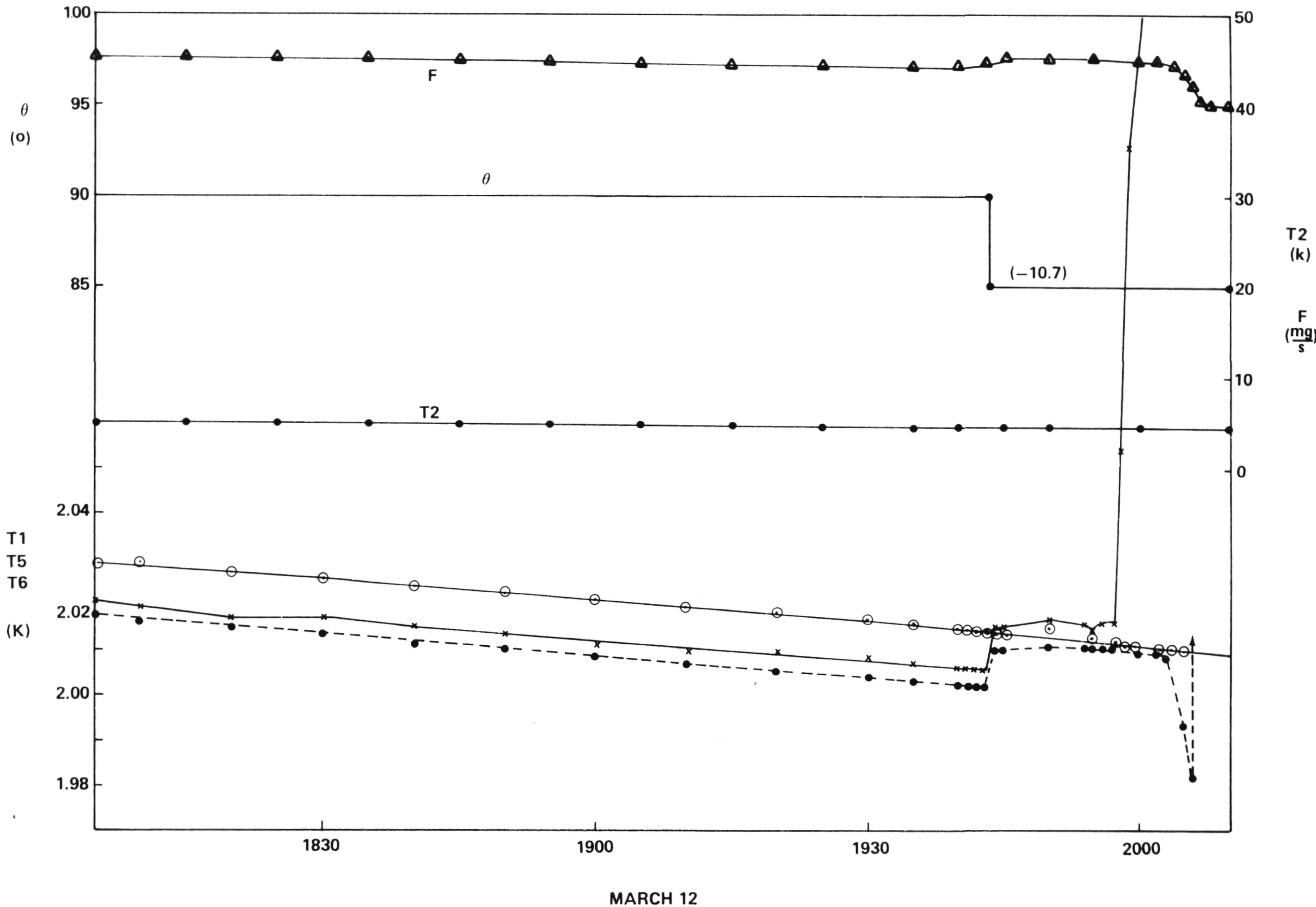

Figure 22. SHe on plug, first test, B, TPE V.

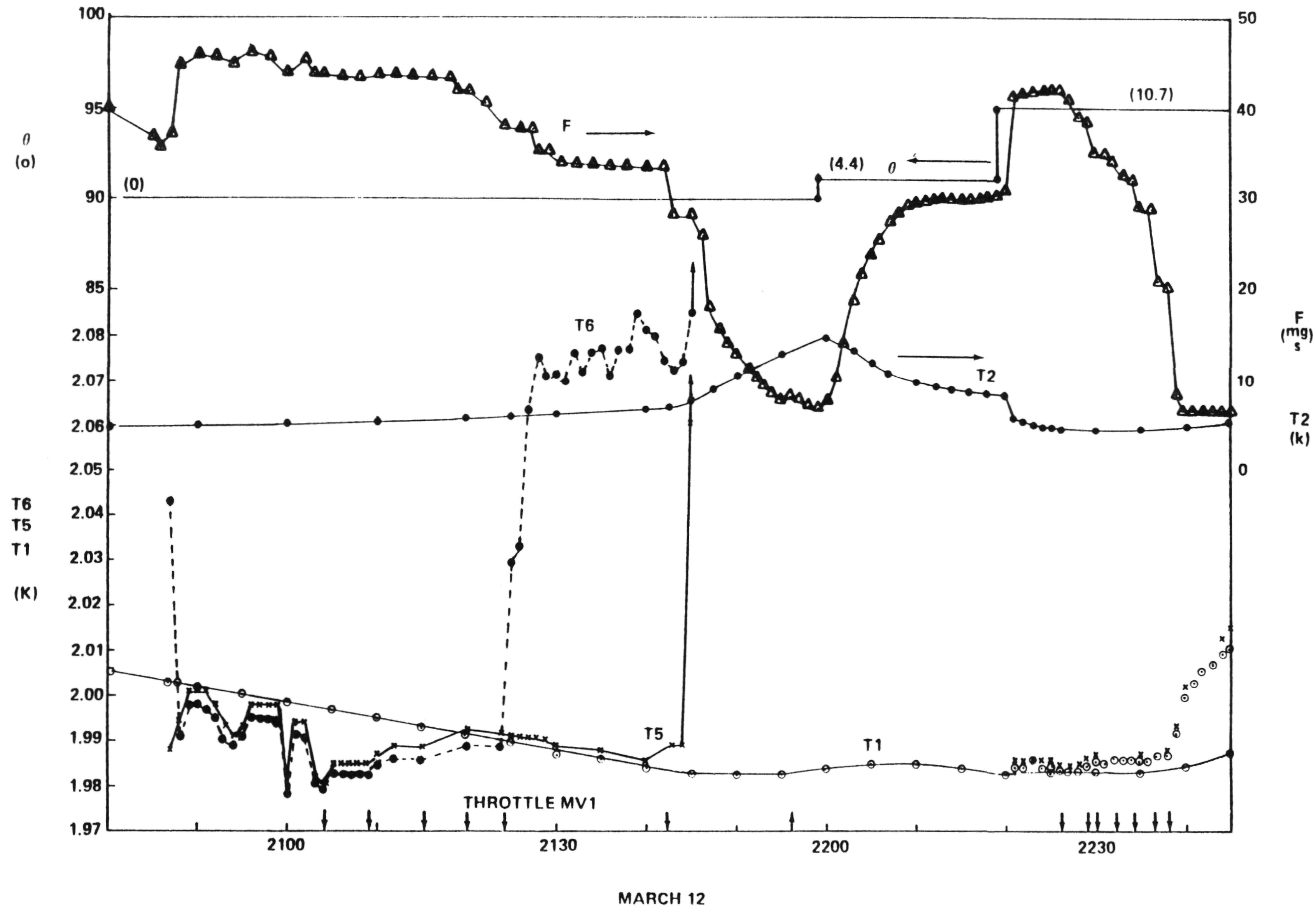

Figure 23. SHe on plug, second test, TPE V.

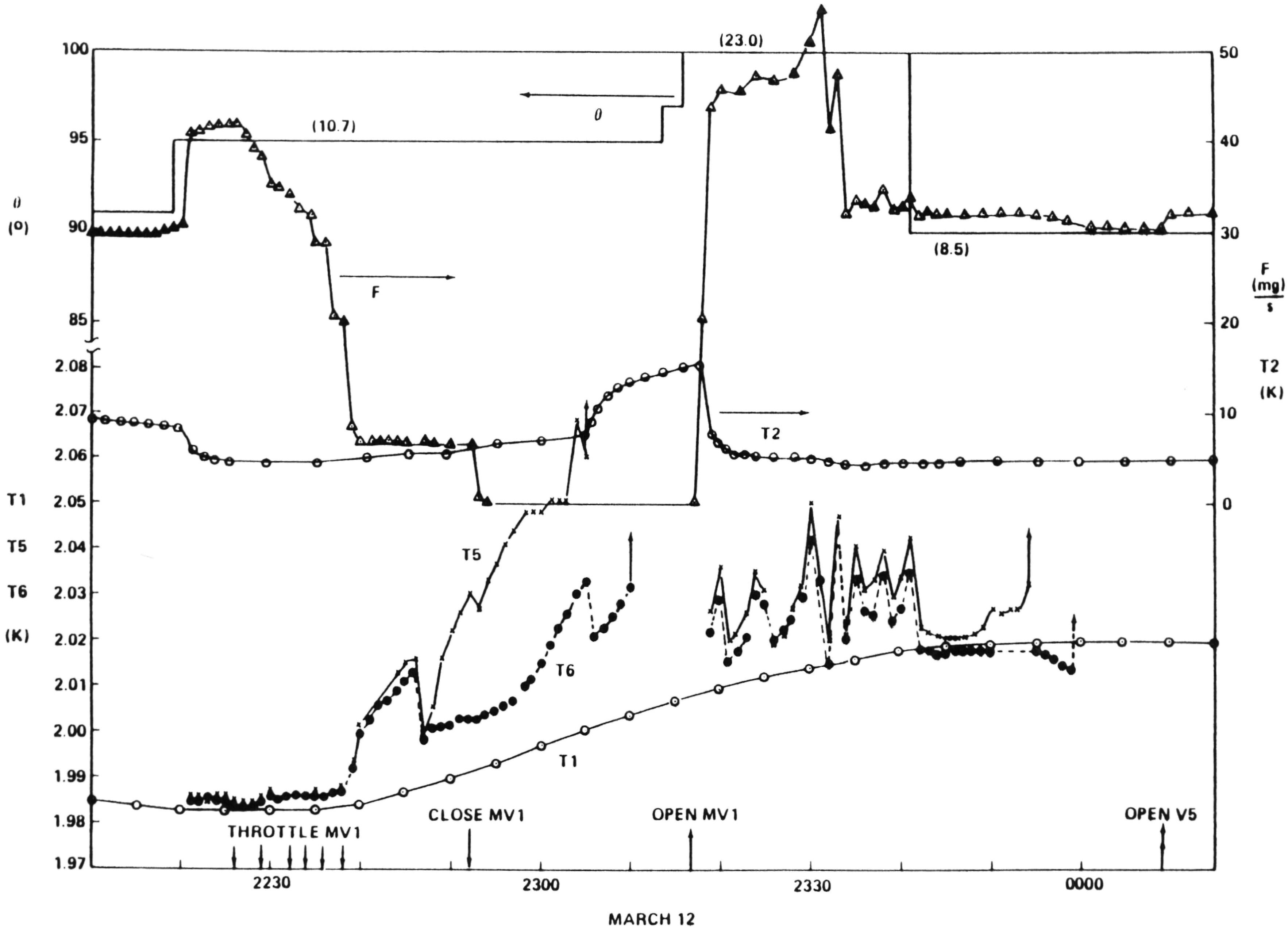

Figure 24. SHe on plug, third and fourth tests, TPE V.

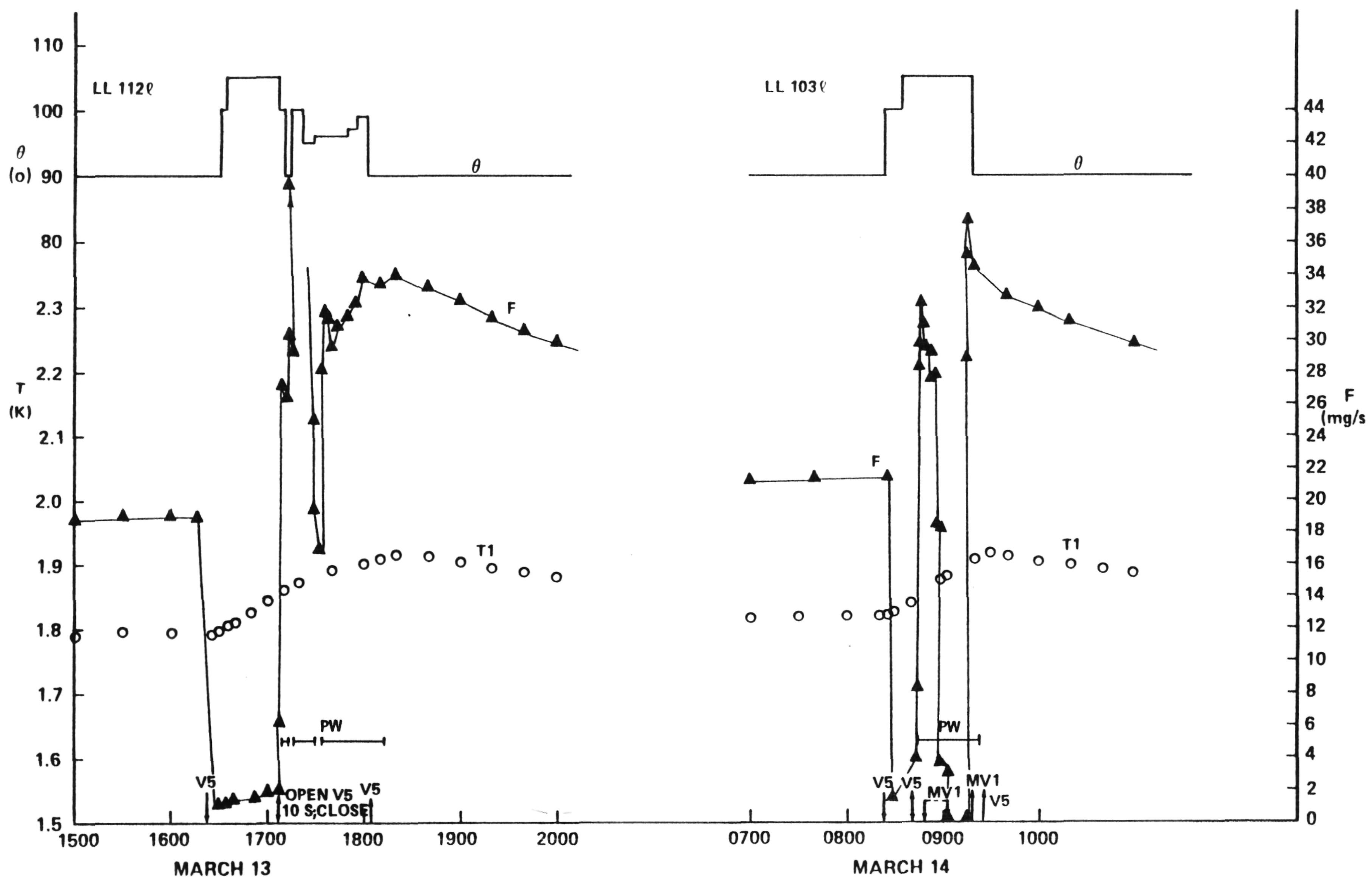

Figure 25. Graphical summary, second and third tilt tests, TPE V.

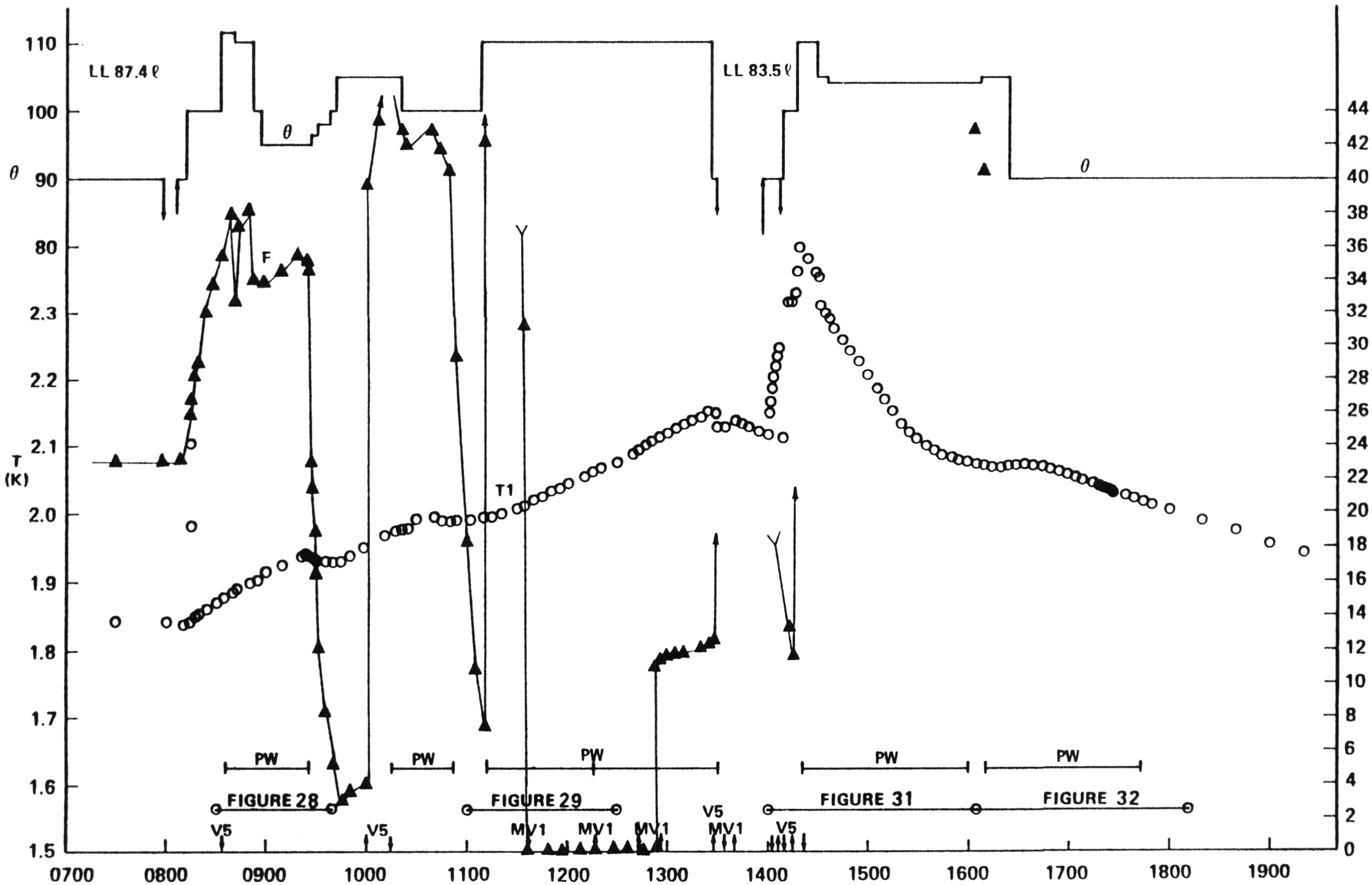

Figure 26. Graphical summary, fourth tilt test, TPE V.

C-2

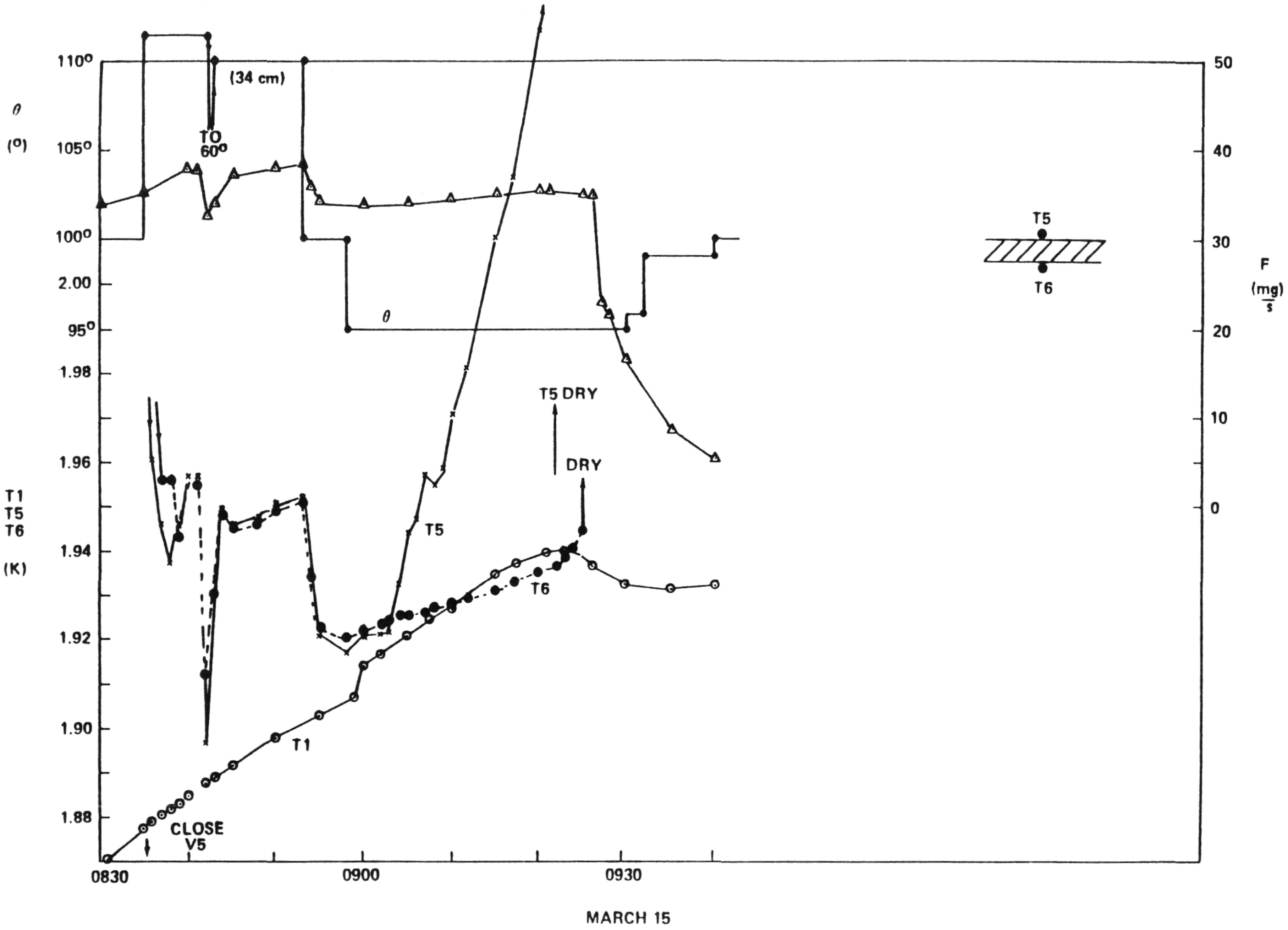

Figure 27. SHe on plug, fifth test, TPE V.

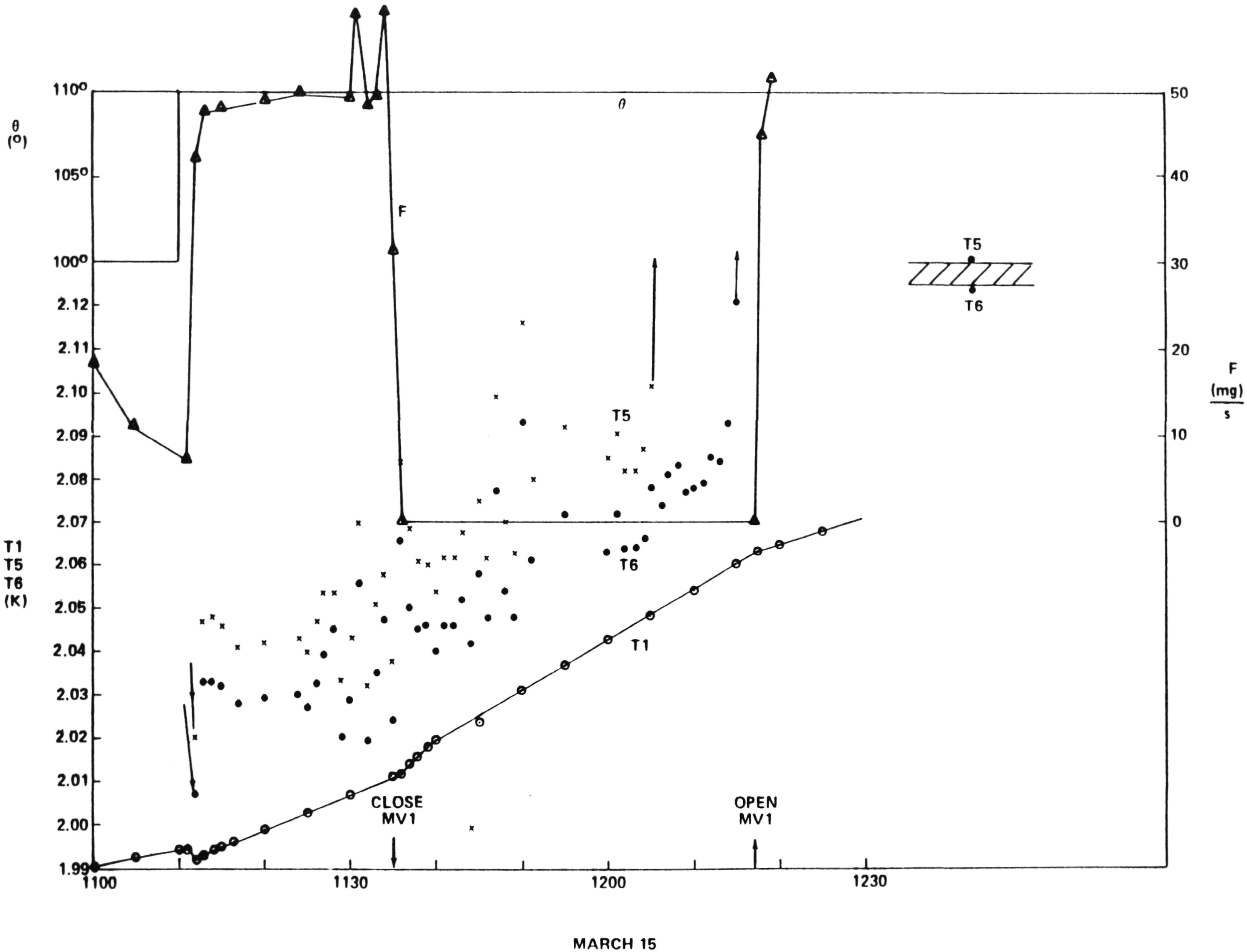

Figure 28. SHe on plug, sixth test, TPE V.

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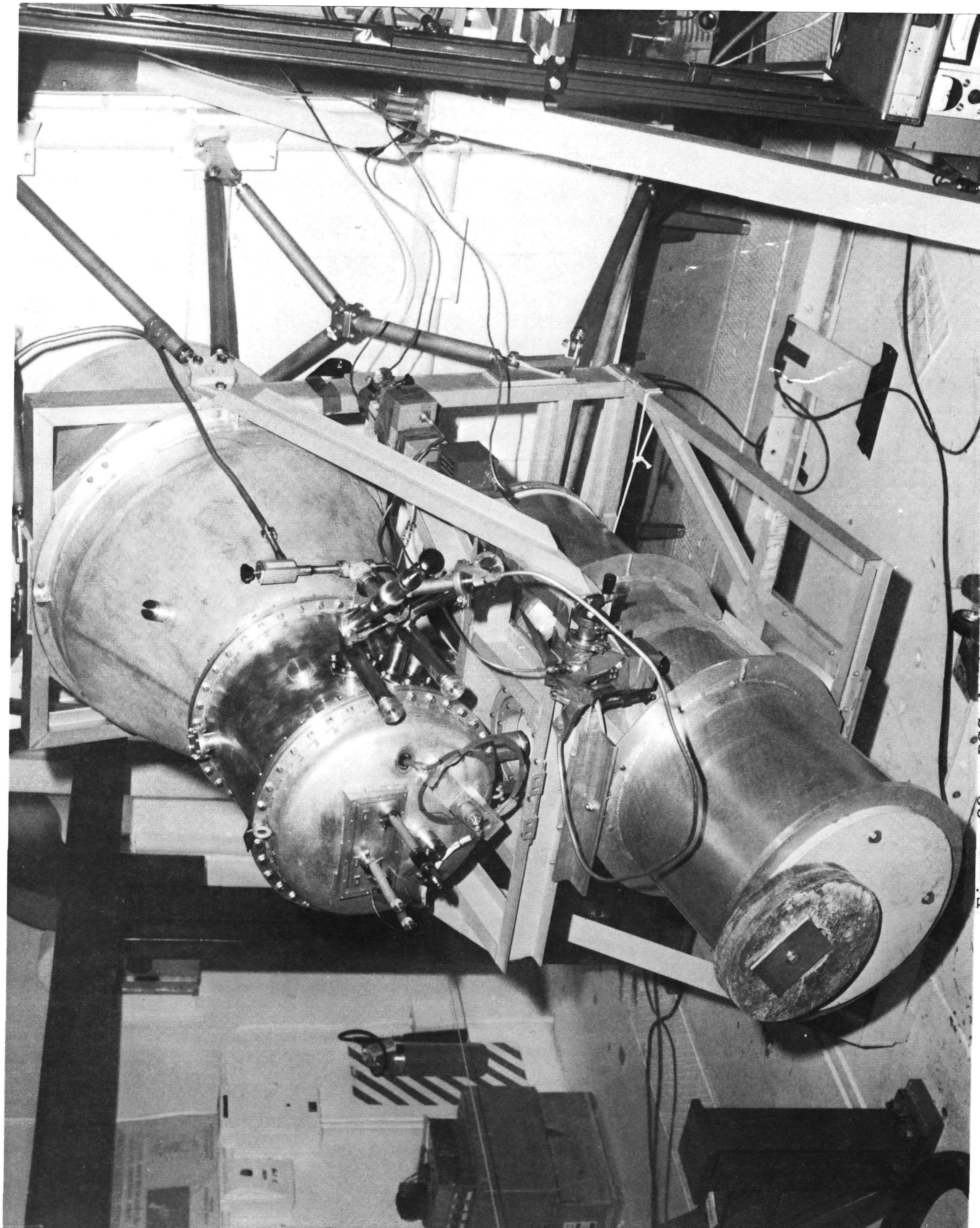

Figure 29. DSS during inverted tilt tests.

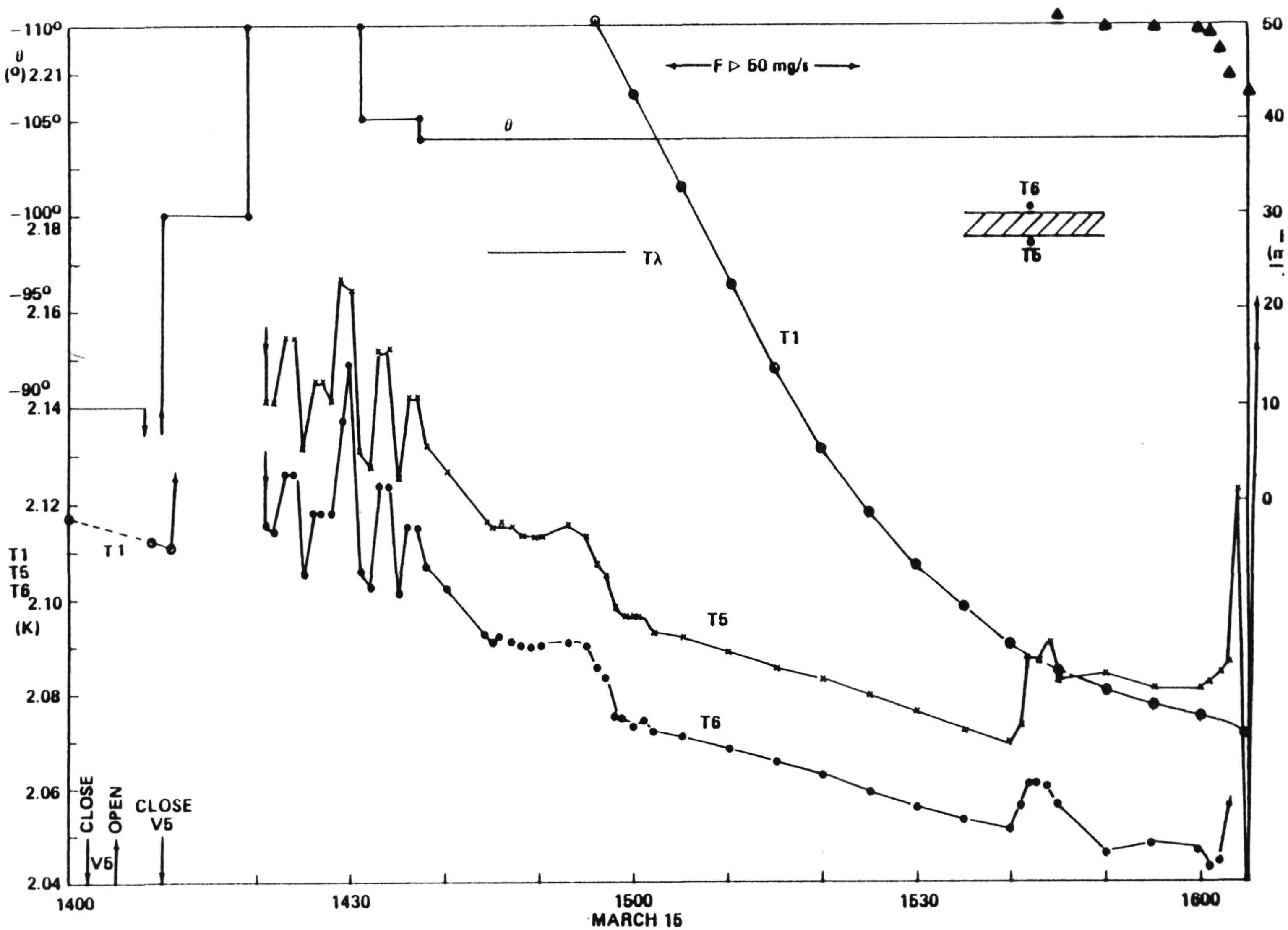

Figure 30. SHe on plug, seventh test, inverted, TPE V.

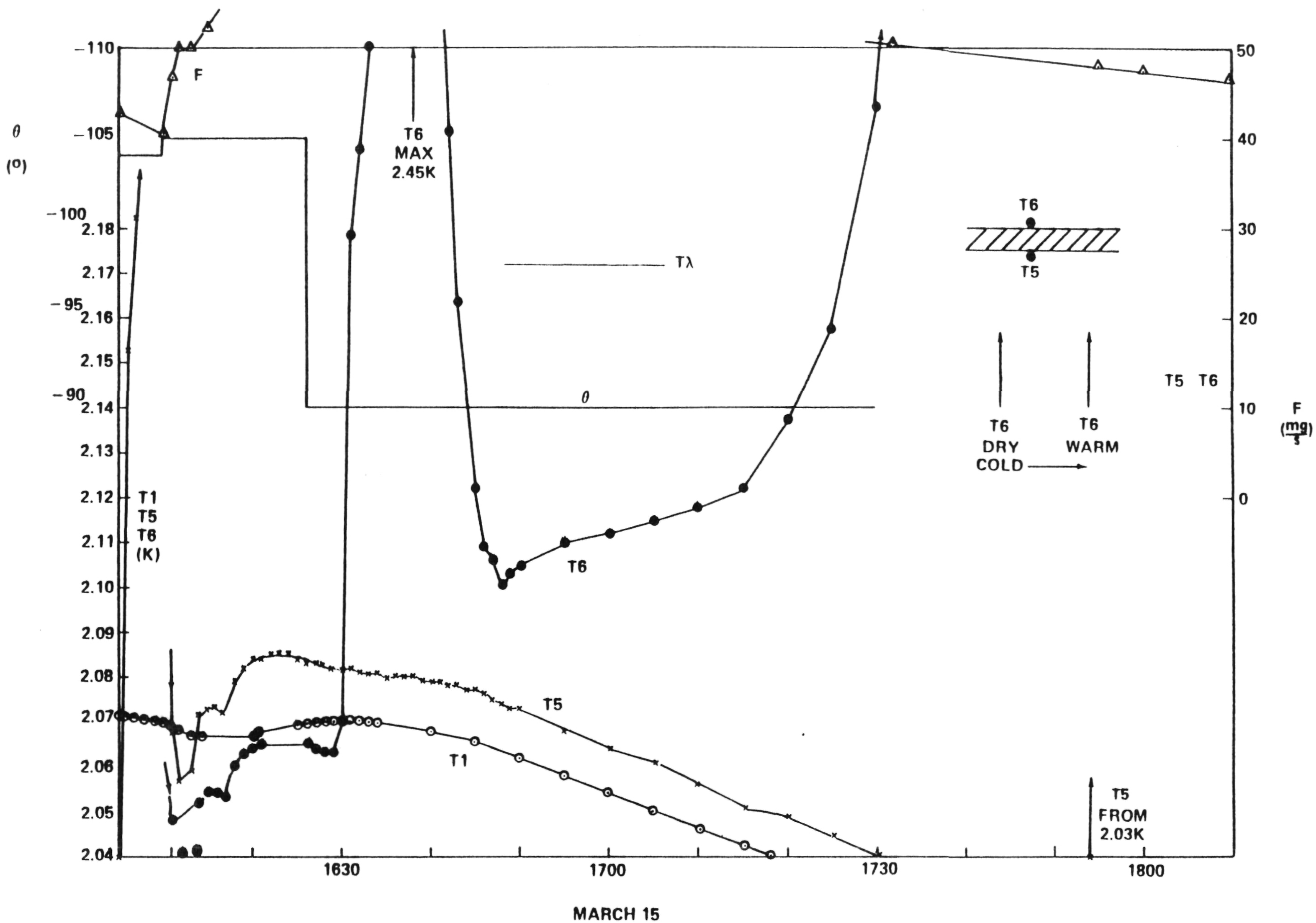

Figure 31. SHe on plug, eighth test, inverted, TPE V.

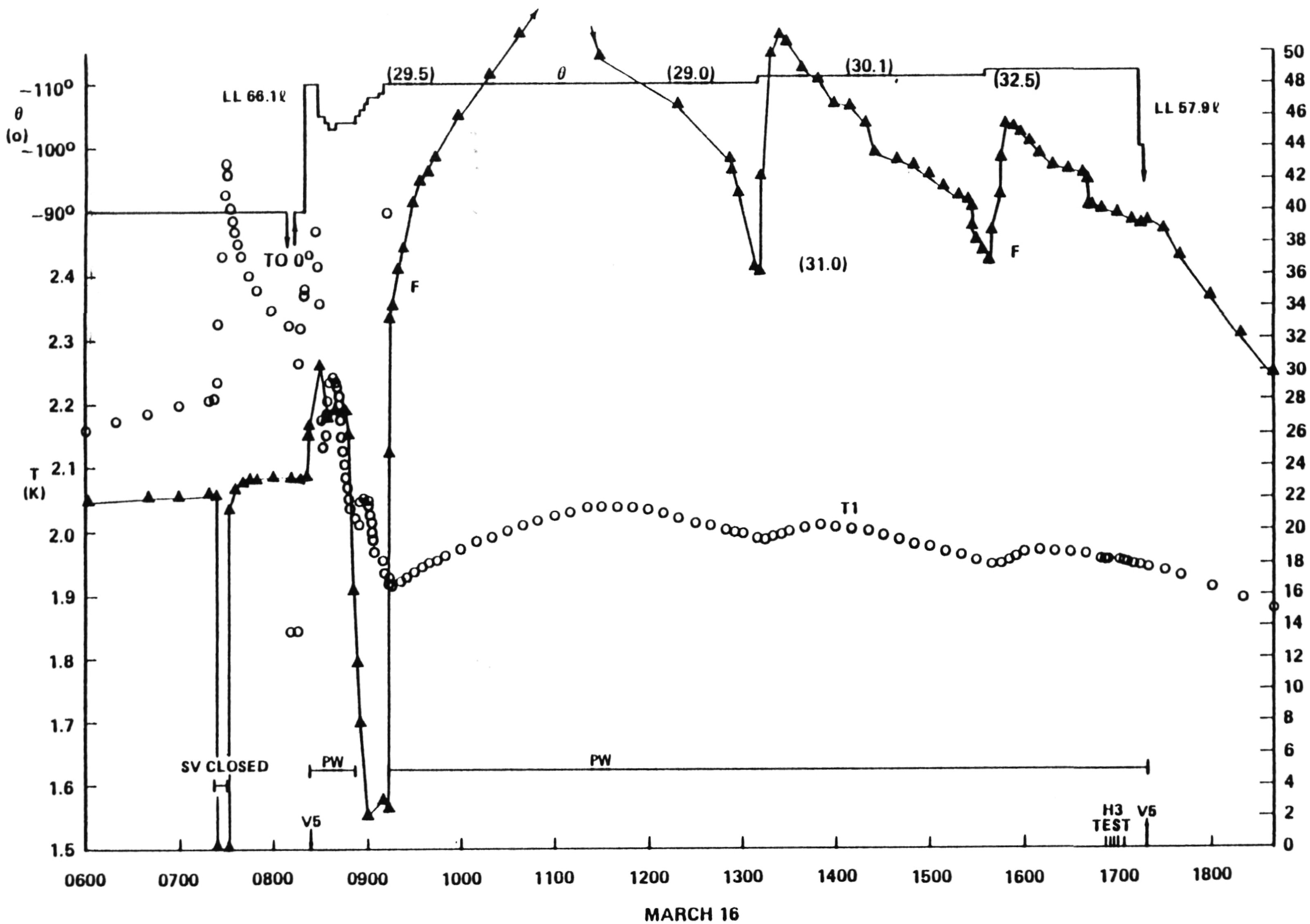

Figure 32. Graphical summary, fifth tilt test, inverted, TPE V.

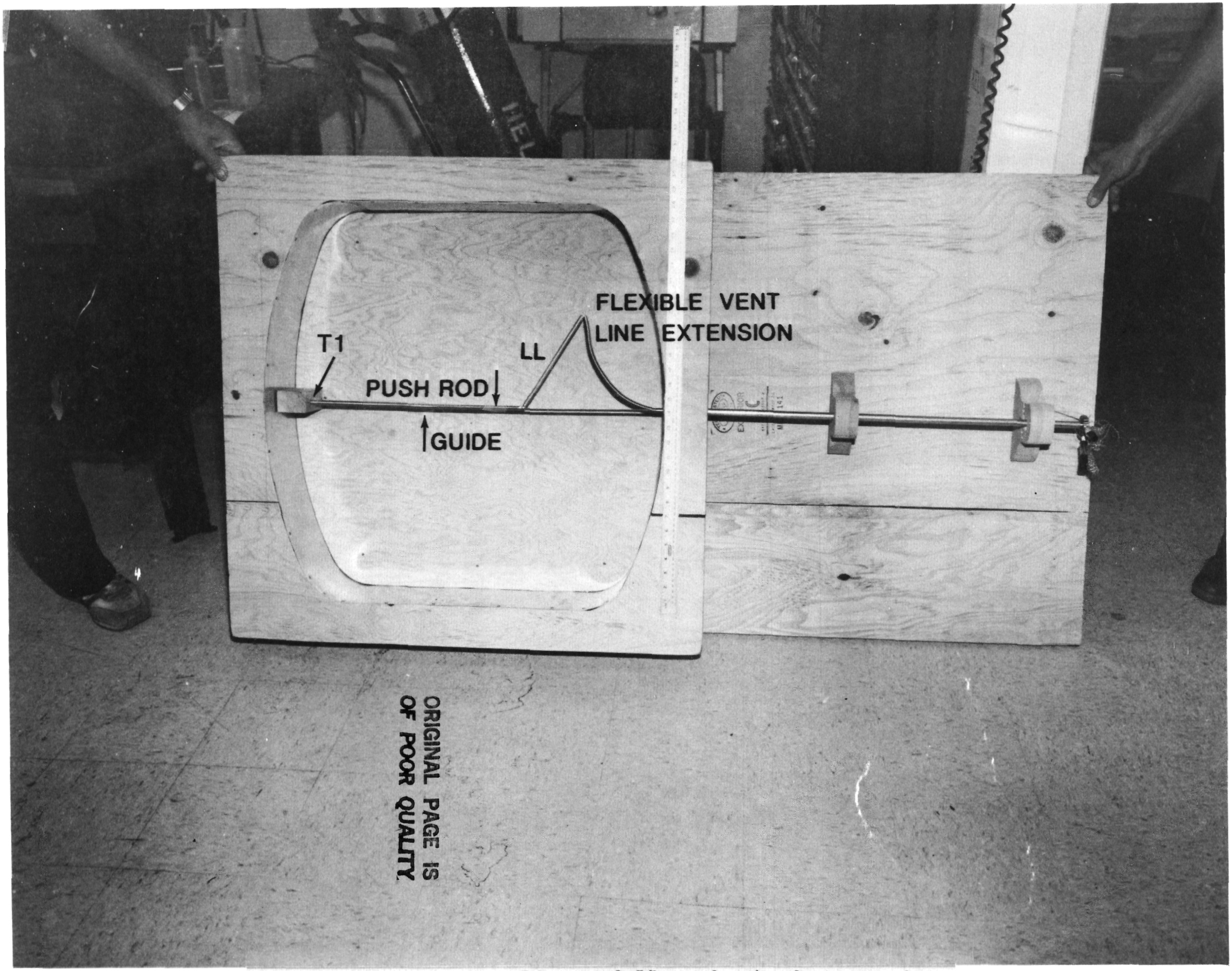

Figure 33. New vent line and LL probe in dewar mockup.

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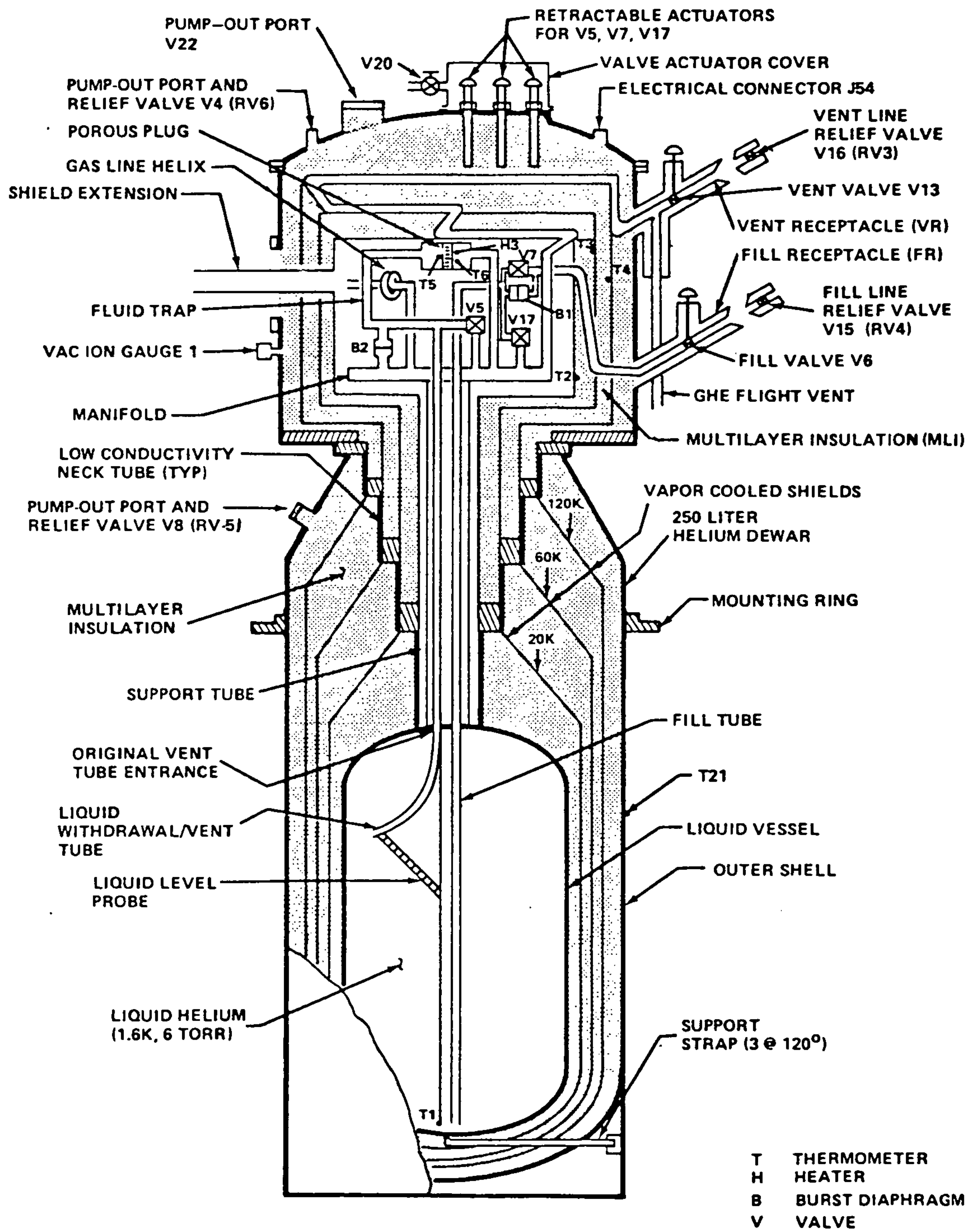

Figure 34. Schematic of IRT dewar subsystem, TPEs VI-VII.

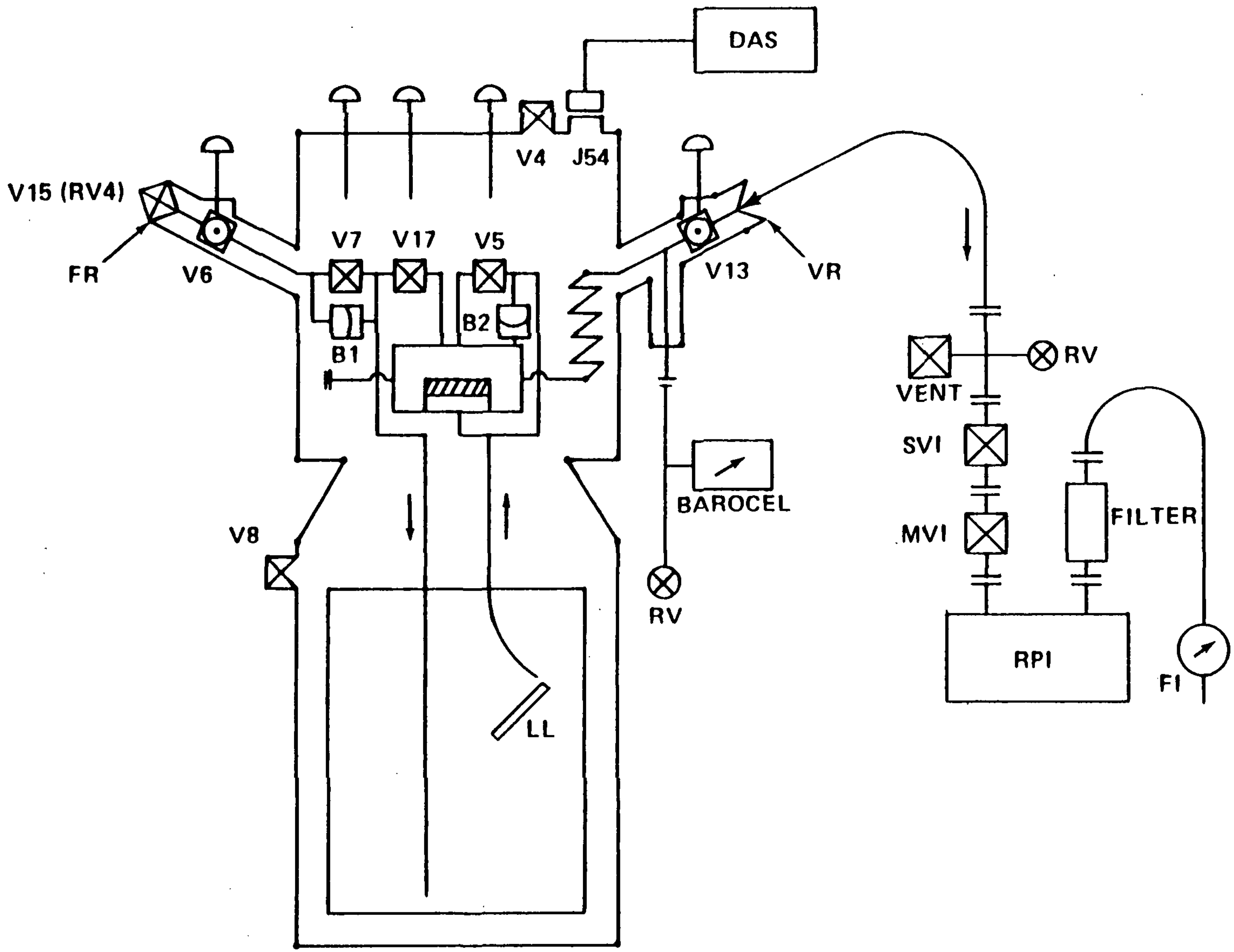

Figure 35. Schematic of TPE VI configuration during conversion and SHe performance test.

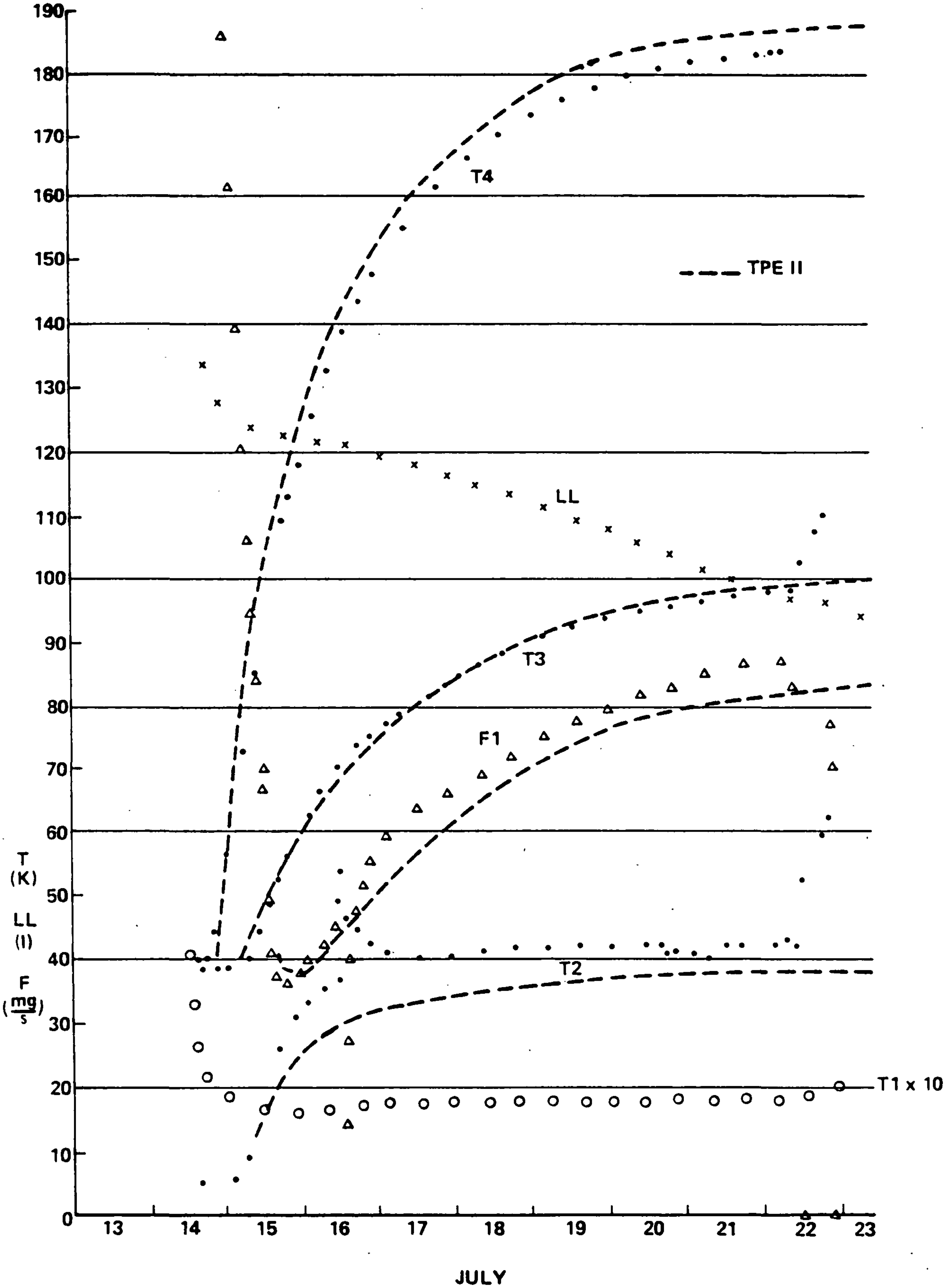

Figure 36. Graphical summary, TPE VI, first phase.

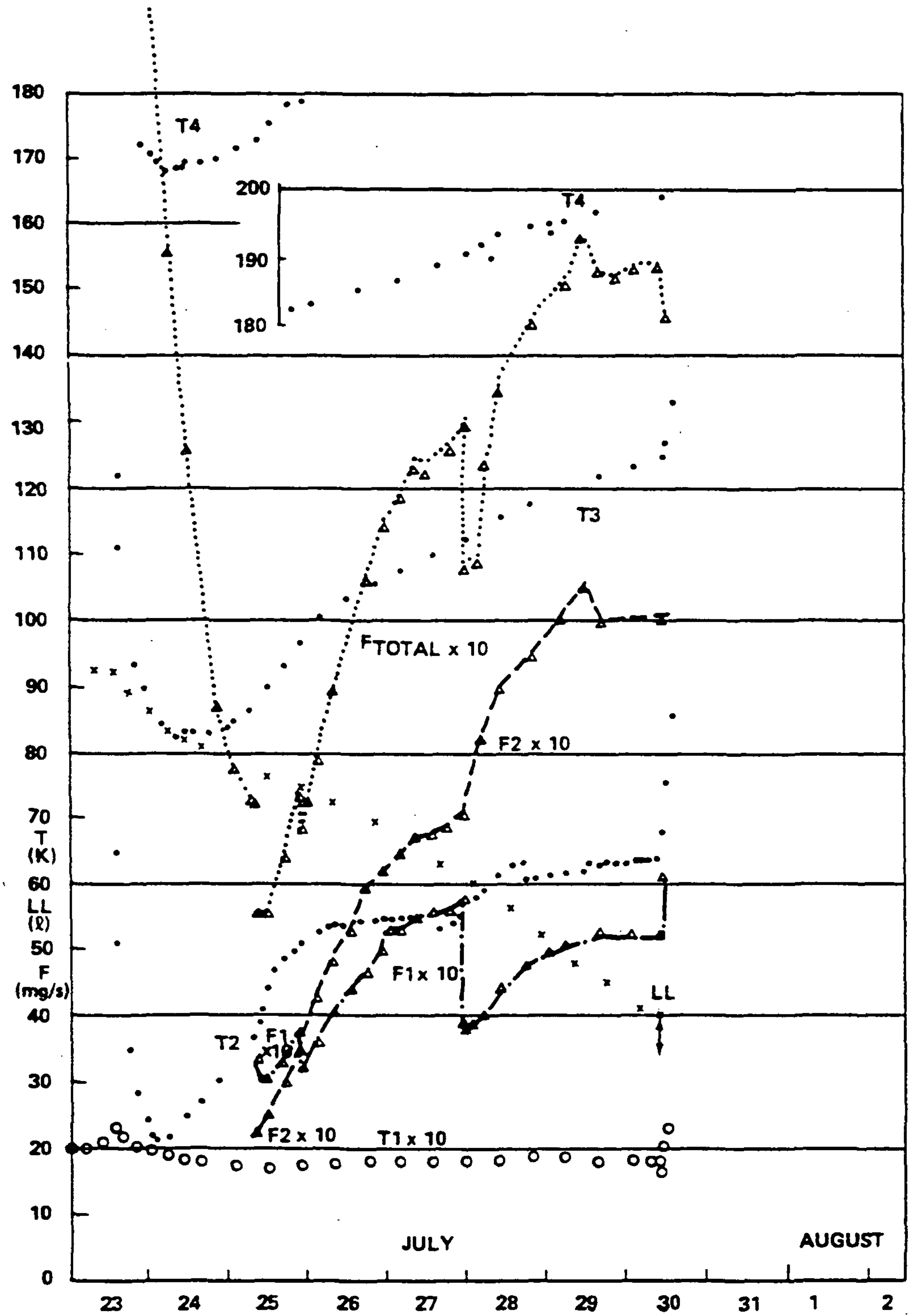

Figure 37. Graphical summary, TPE VI, second phase.

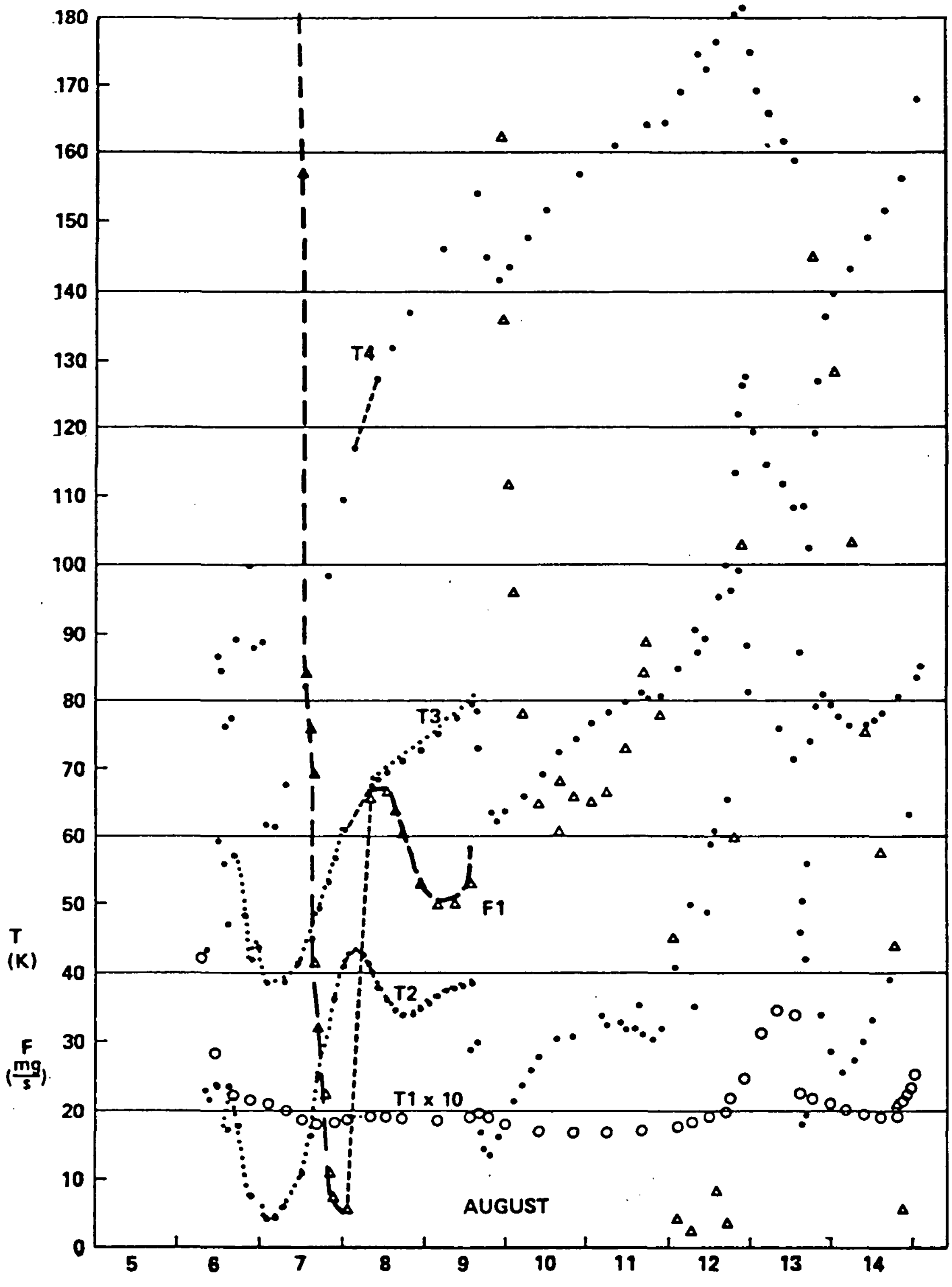

Figure 38. Graphical summary, TPE VII.

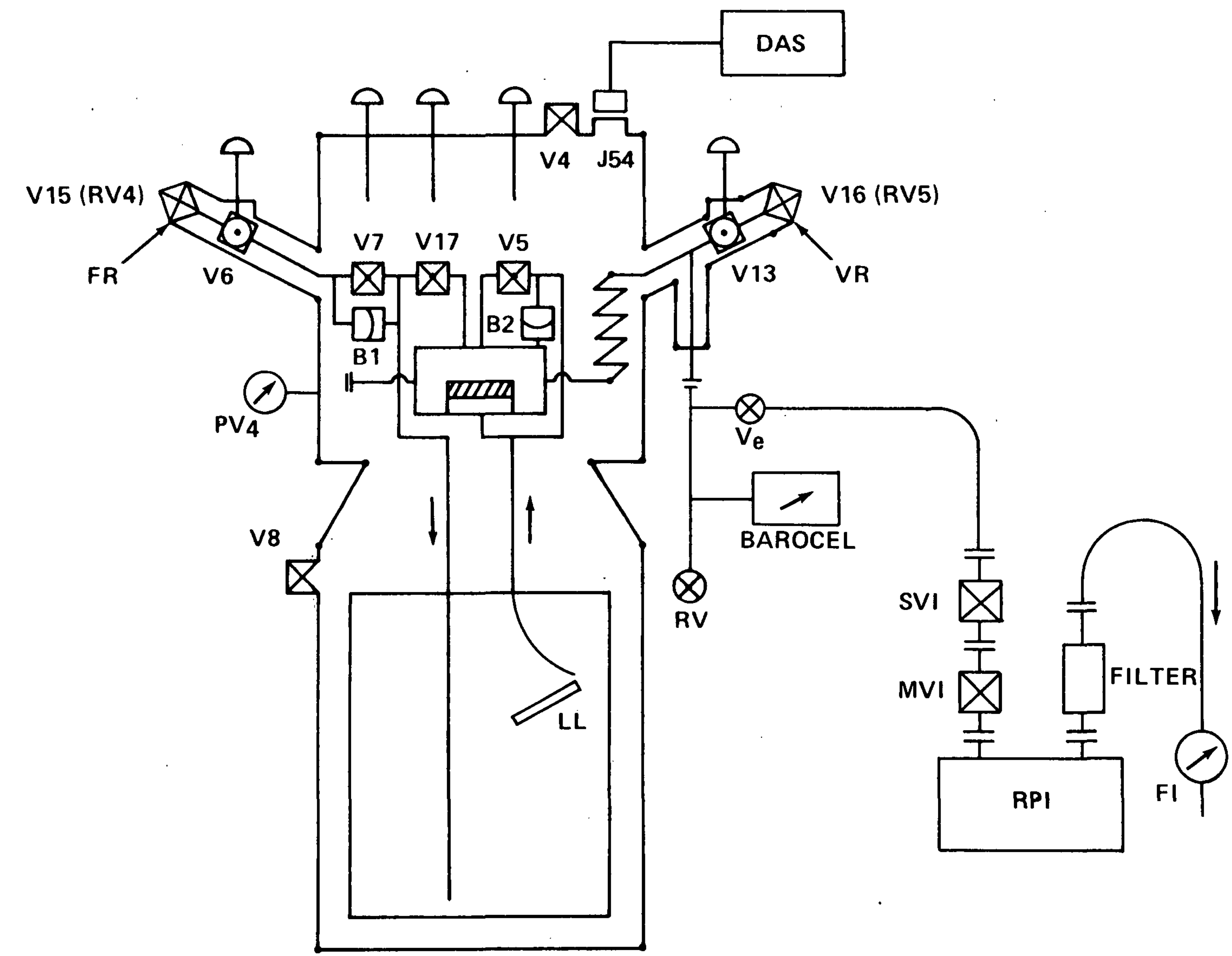

Figure 39. Schematic of TPE VII configuration during SHe performance test.

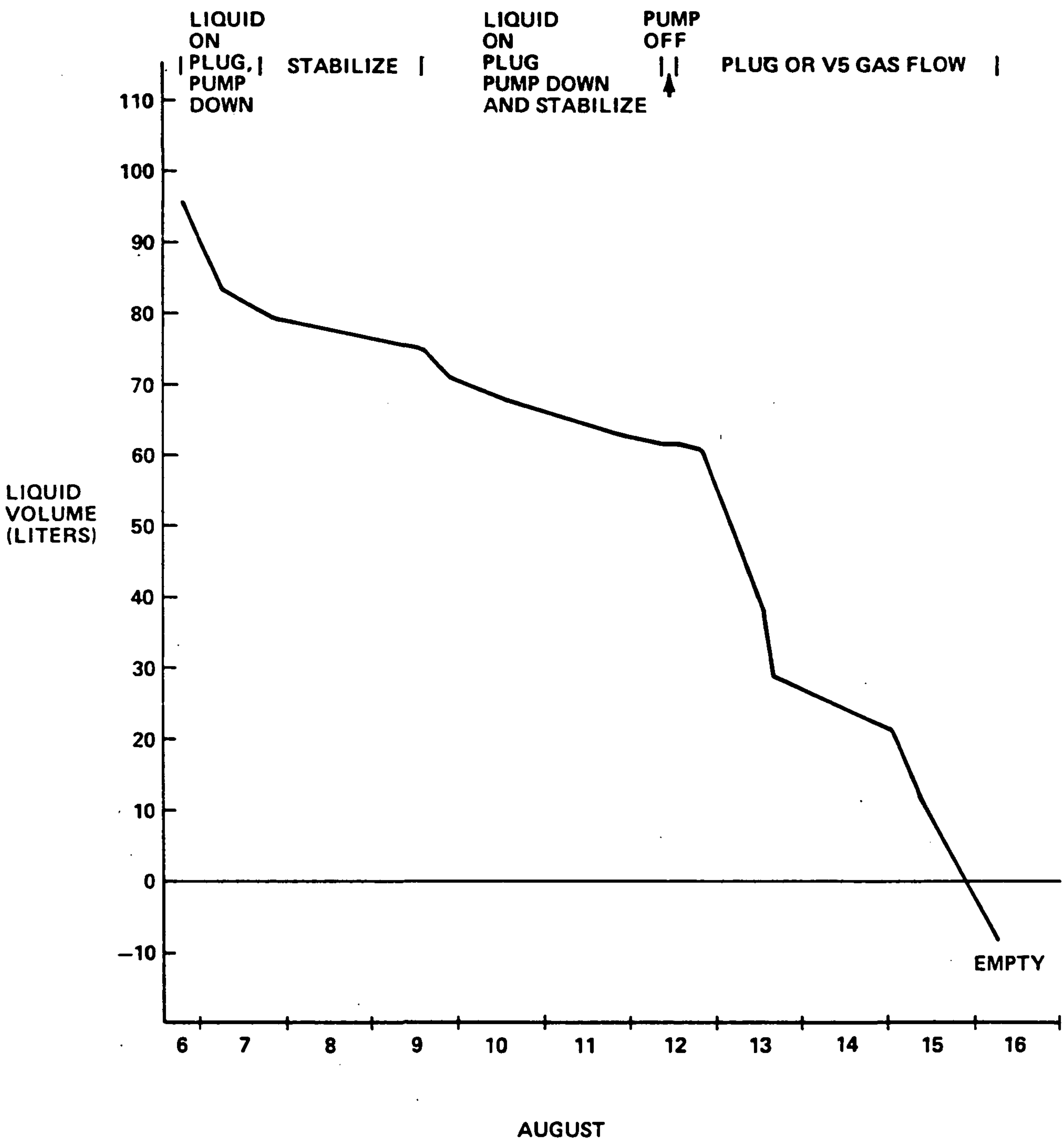

Figure 40. Calculated liquid volume, TPE VII.

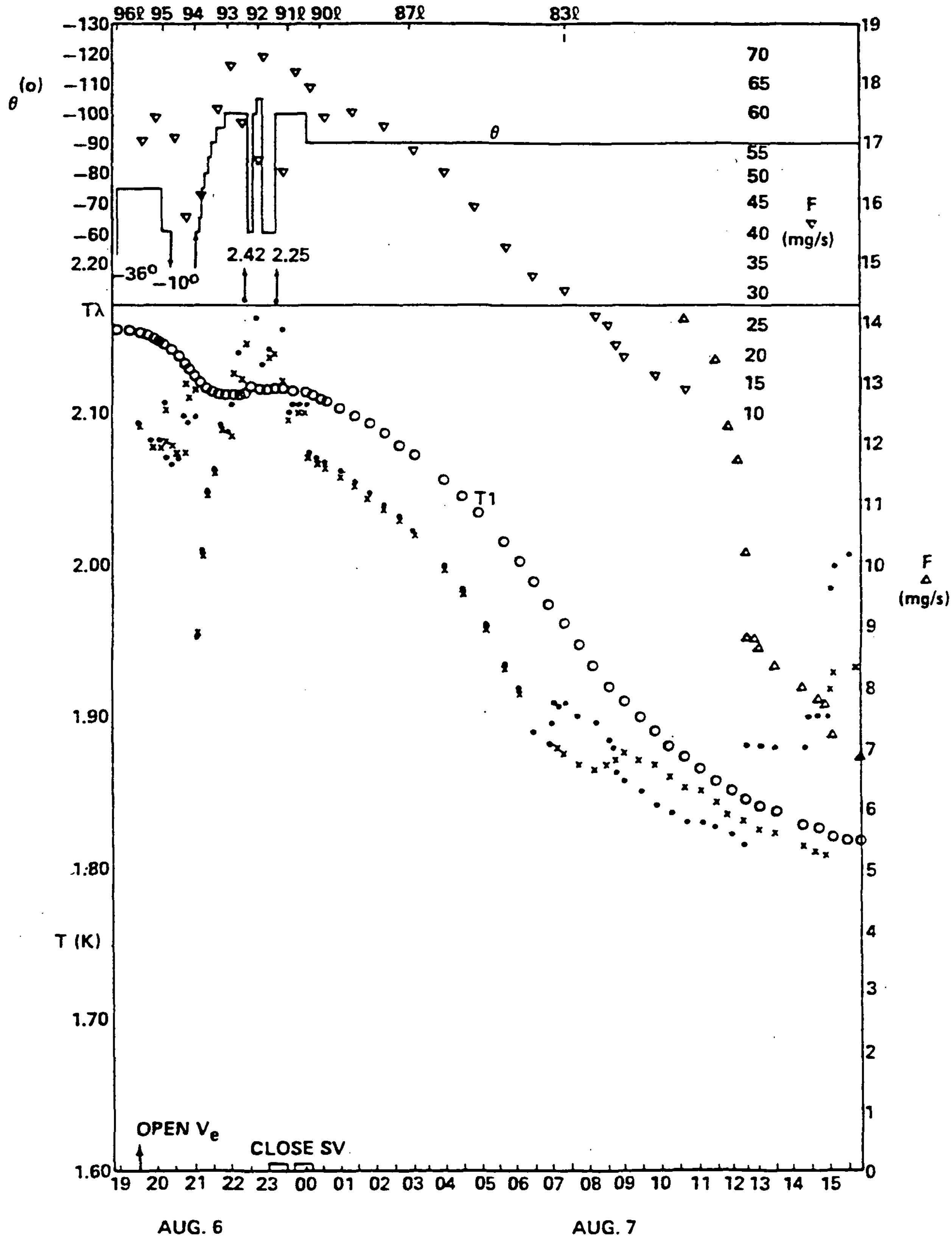

Figure 41. Graphical summary, first tilt test, TPE VII.

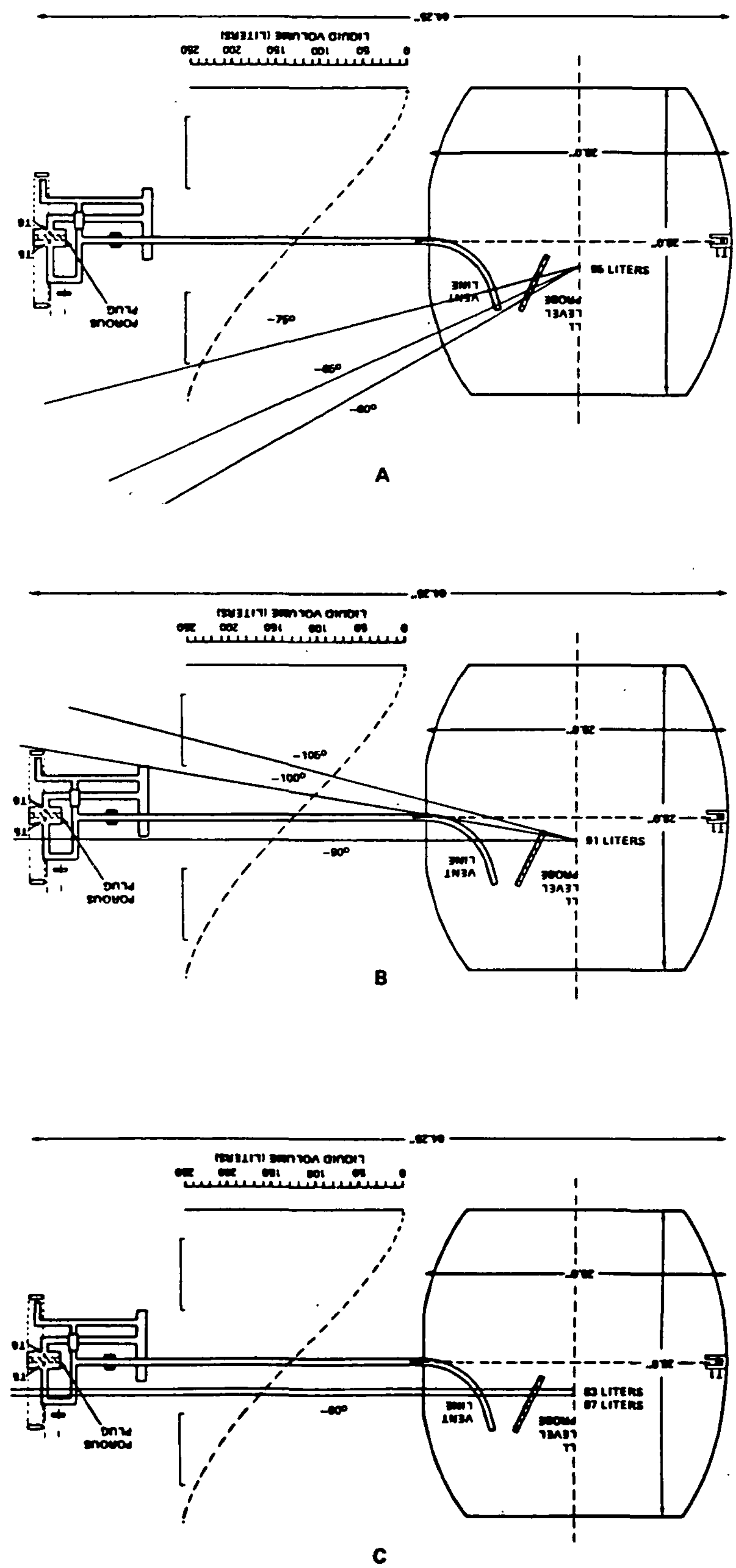

Figure 42. Tilt angles and liquid levels, first tilt test, TPE VII.

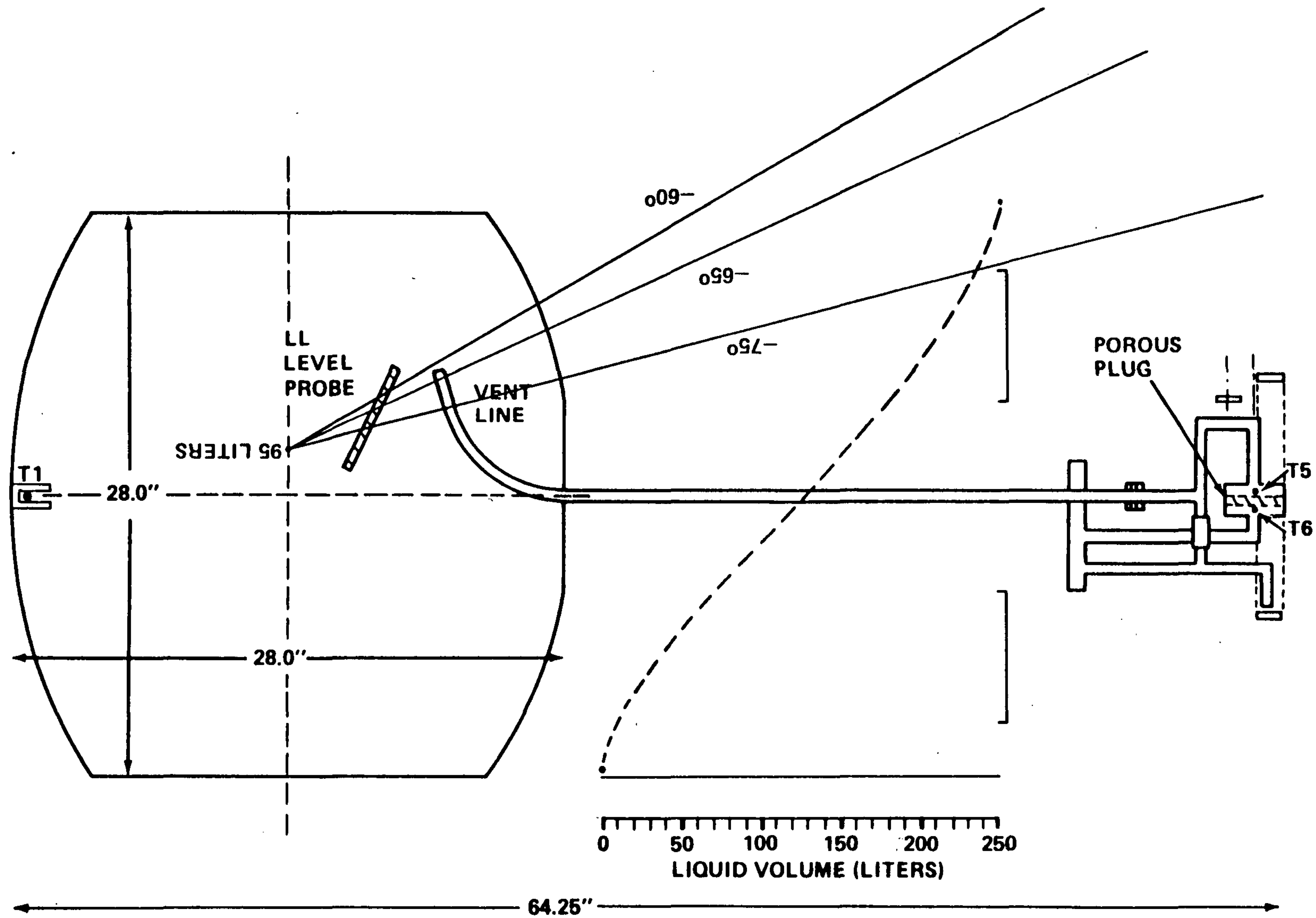

Figure 42a. Tilt angles and liquid levels, first tilt test, TPE VII.

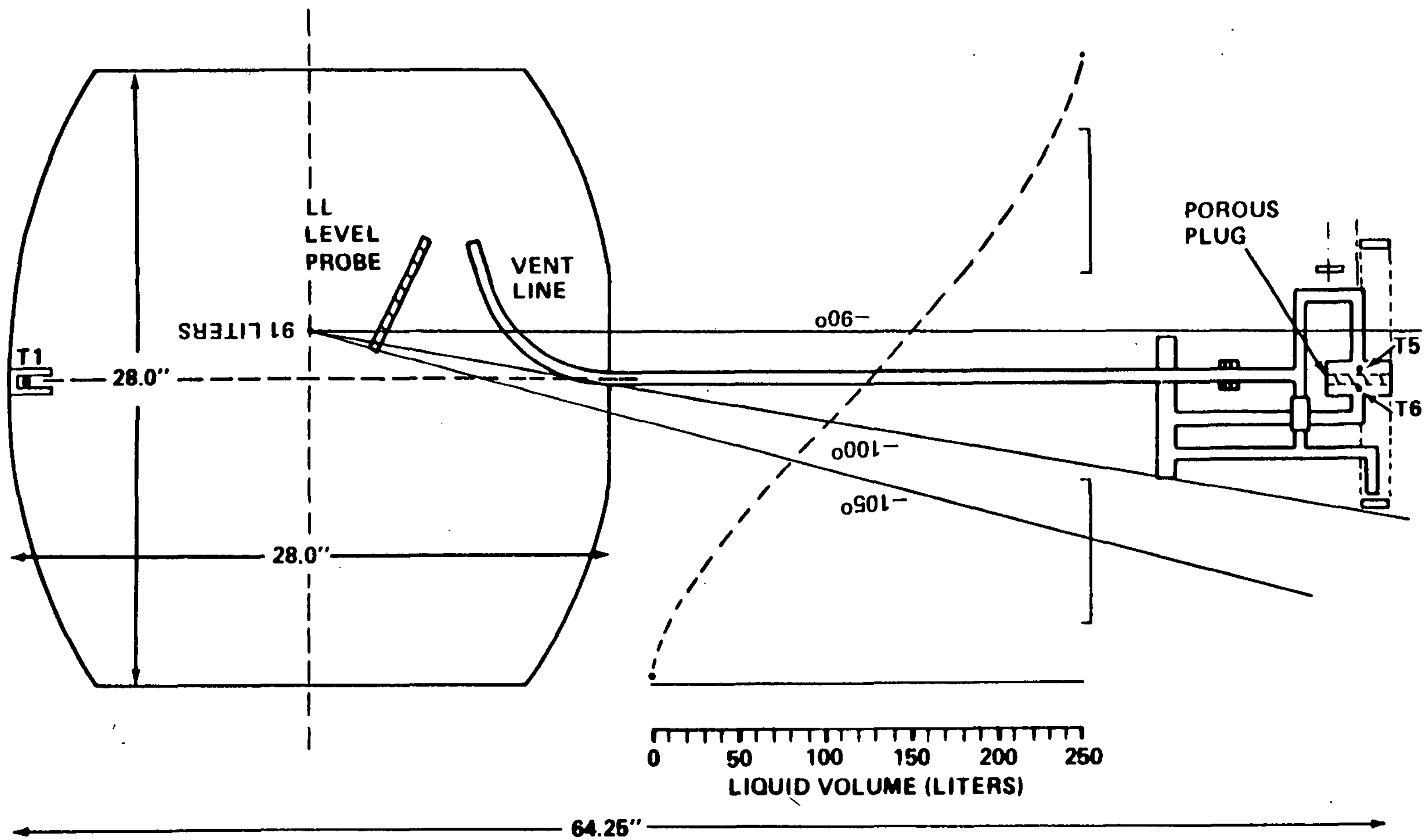

Figure 42b. Tilt angles and liquid levels, first tilt test, TPE VII.

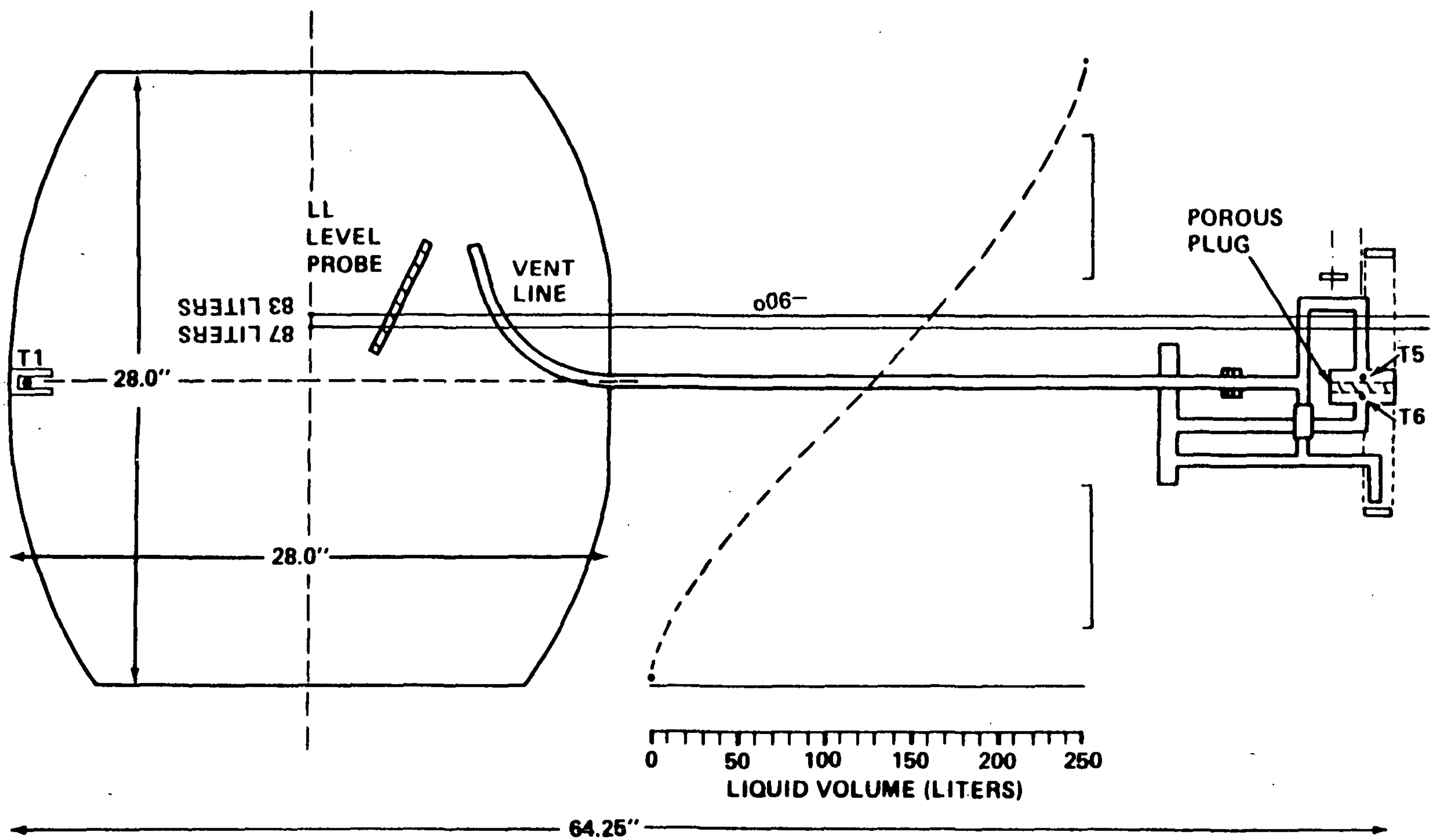

Figure 42c. Tilt angles and liquid levels, first tilt test, TPE VII.

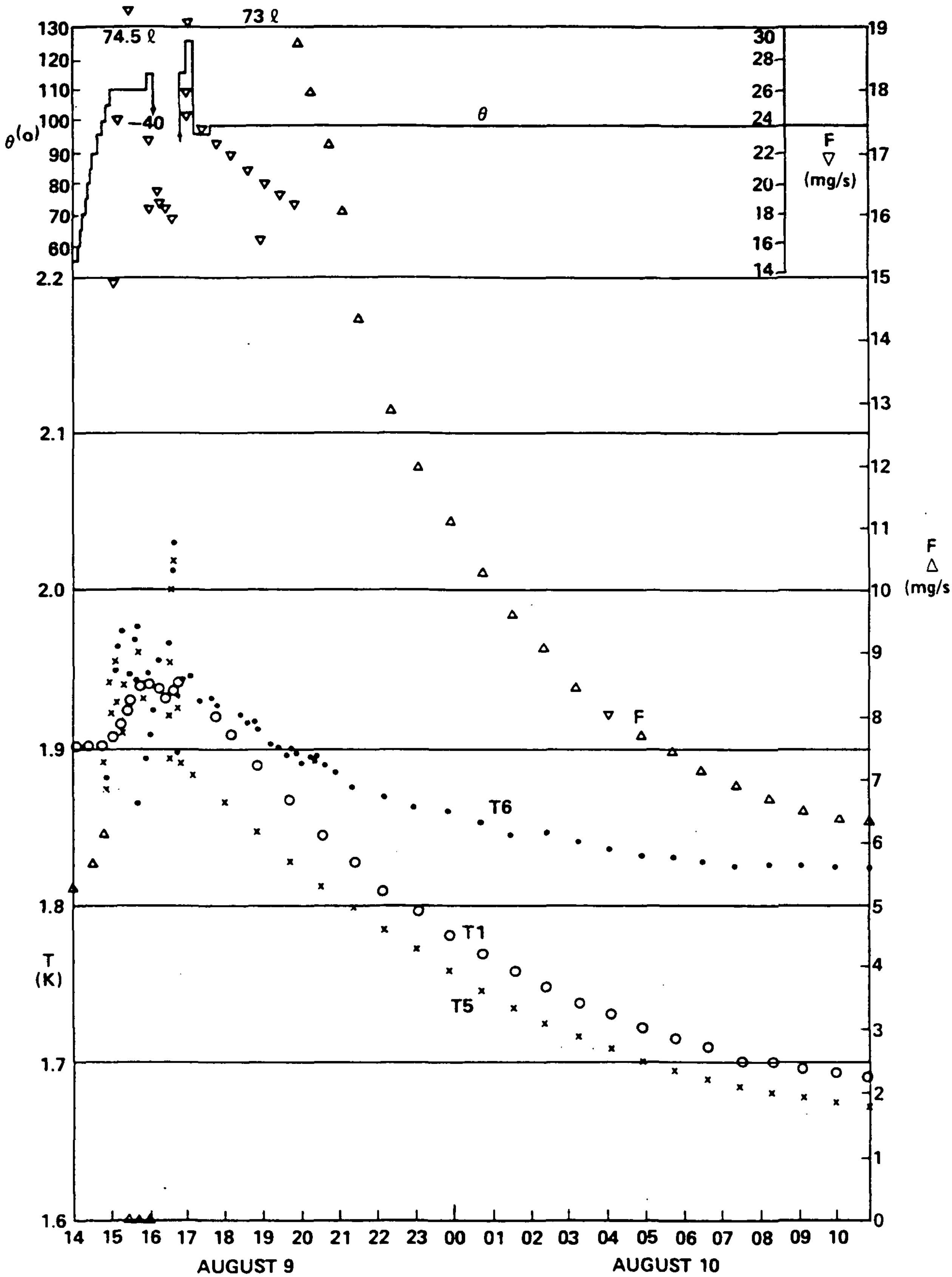

Figure 43. Graphical summary, second tilt test, first phase, TPE VII.

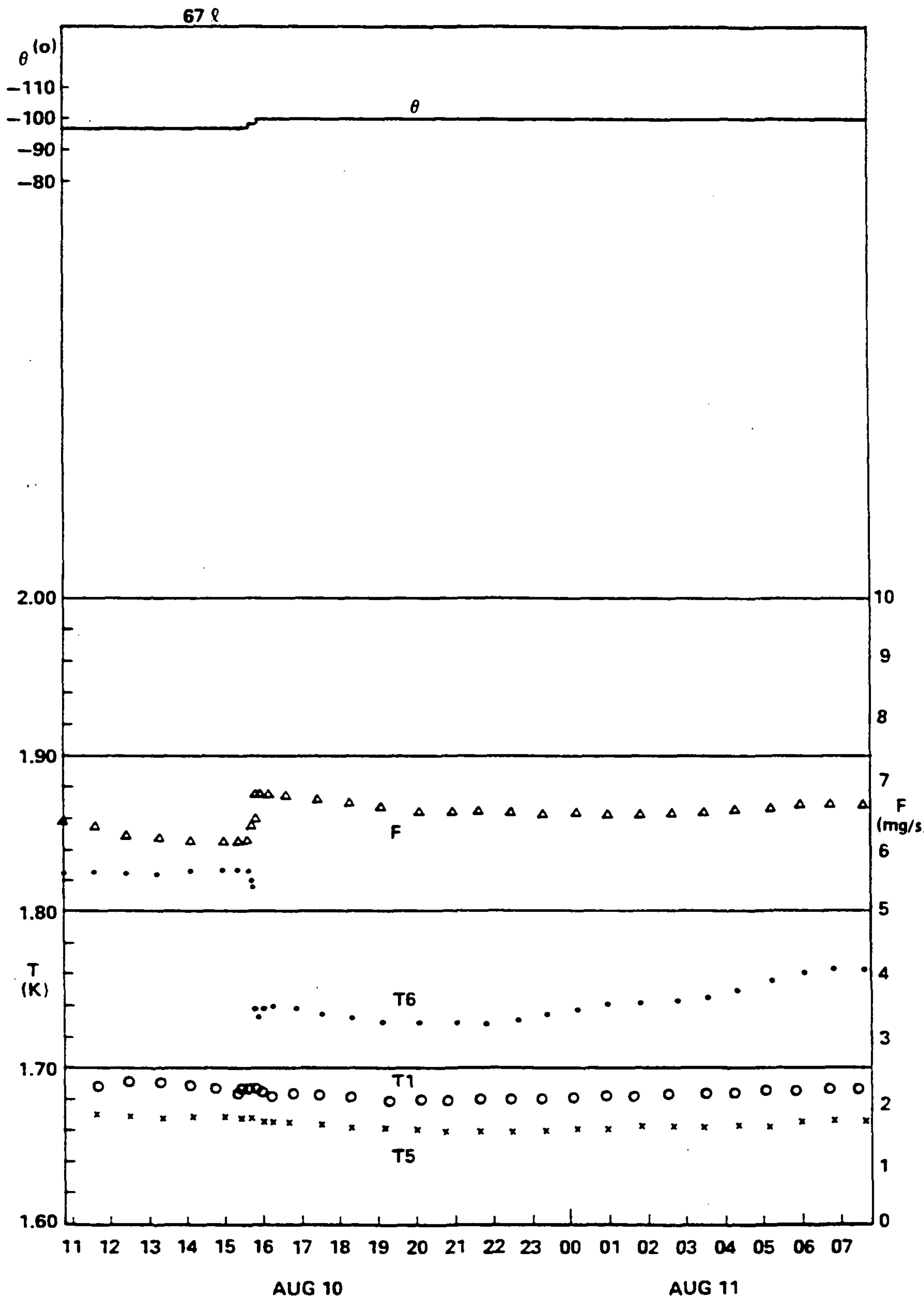

Figure 44. Graphical summary, second tilt test, second phase, TPE VII.

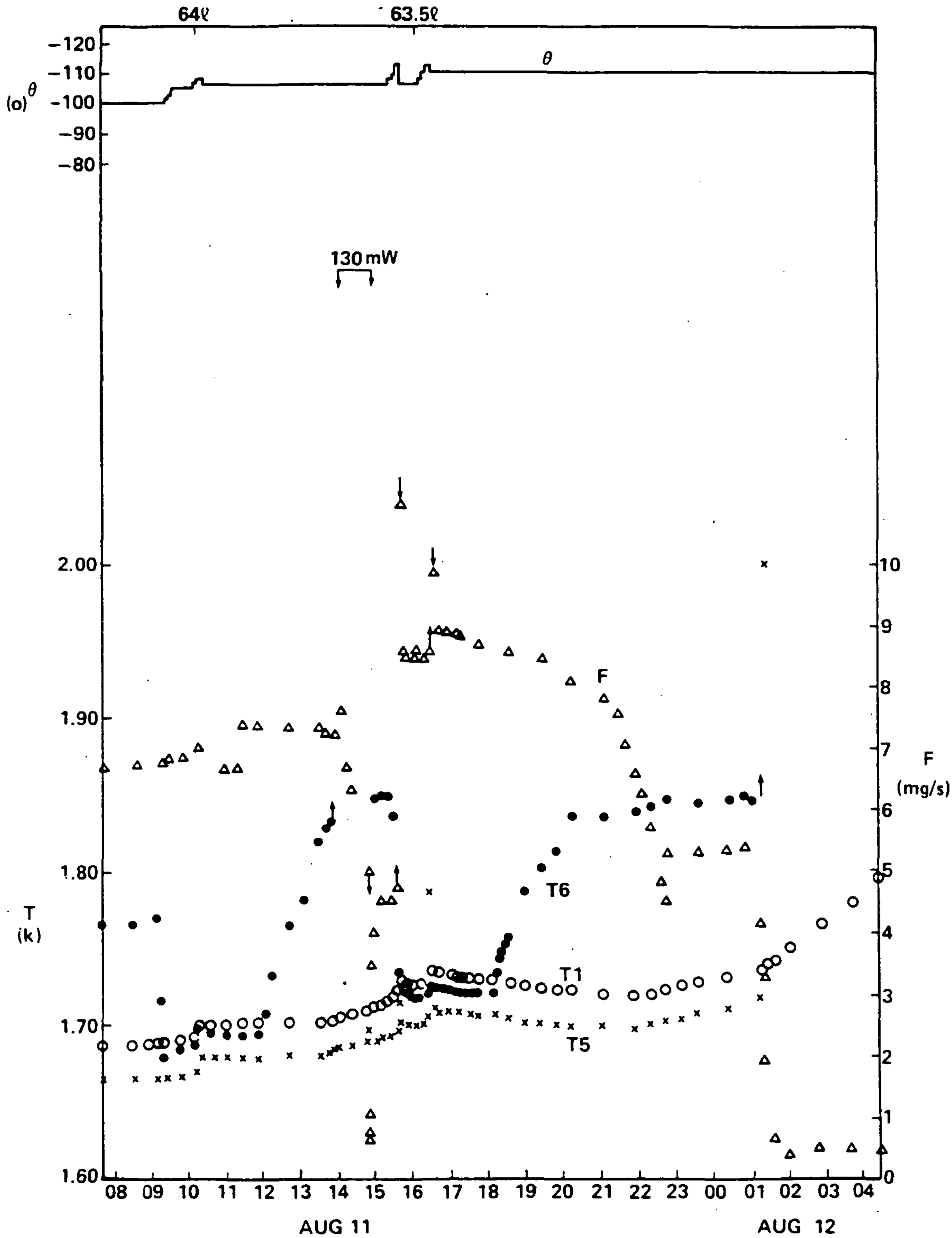

Figure 45. Graphical summary, second tilt test, third phase, TPE VII.

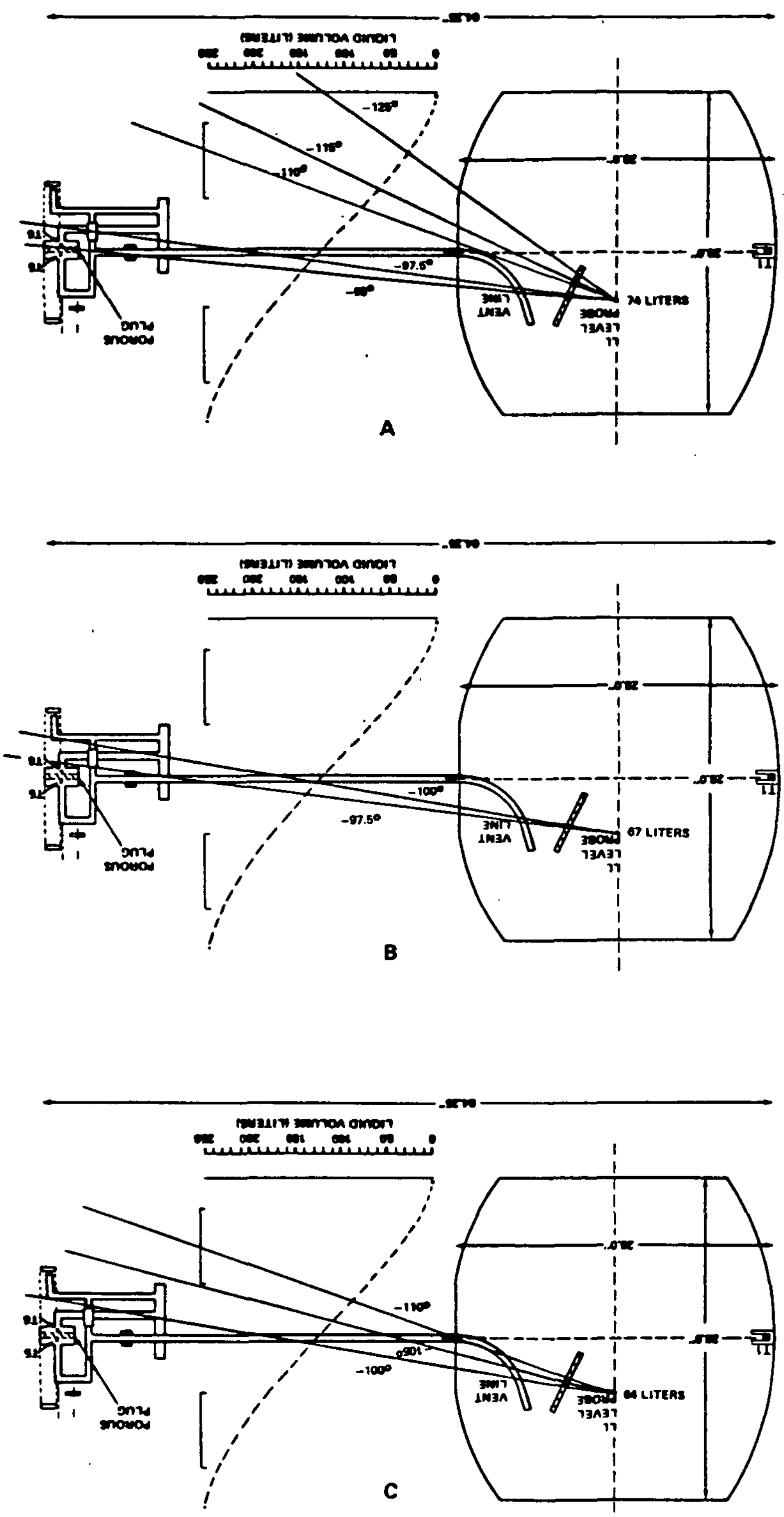

Figure 46. Tilt angles and liquid levels, second tilt test, TPE VII.

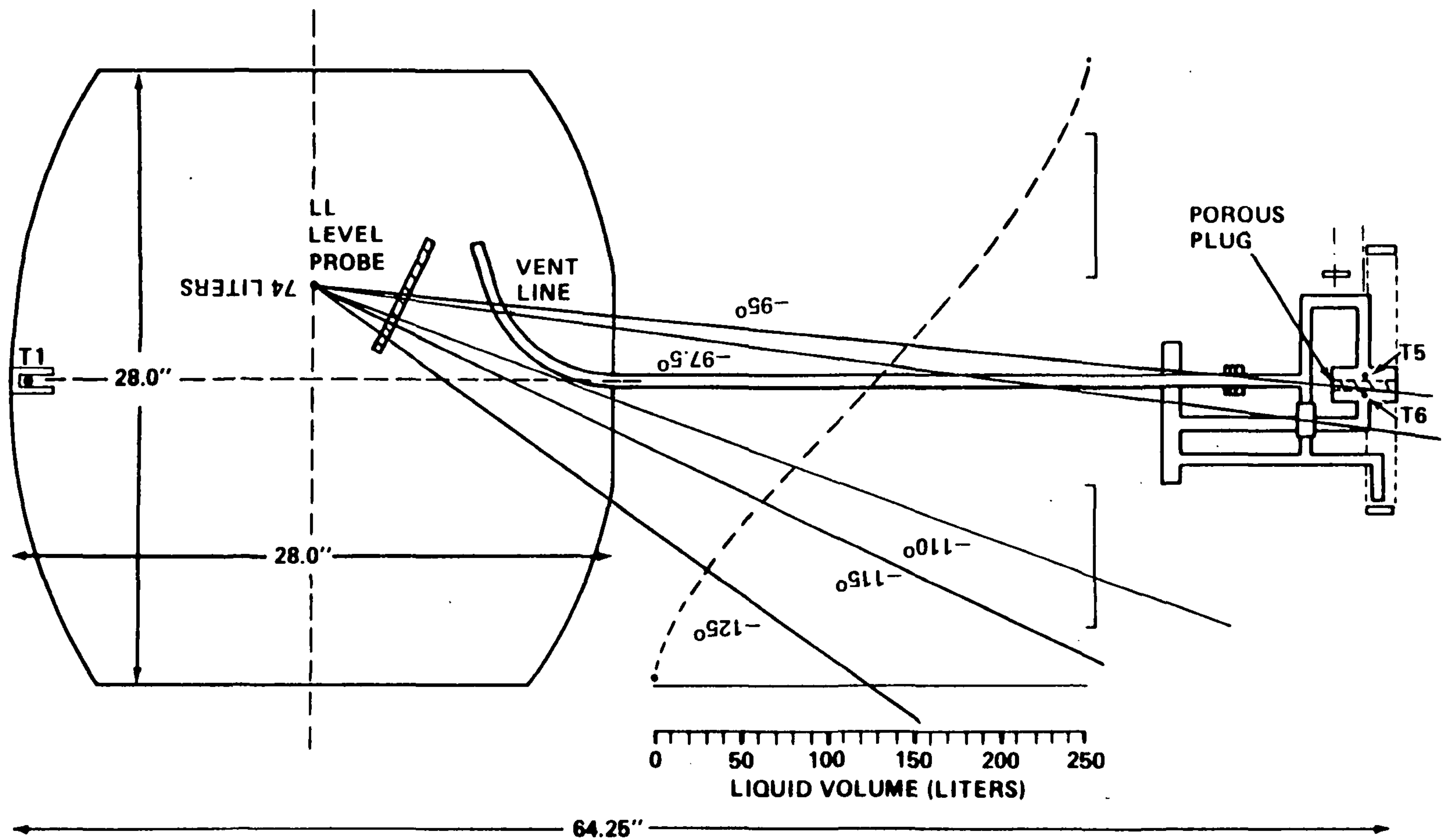

Figure 46a. Tilt angles and liquid levels, second tilt test, TPE VII.

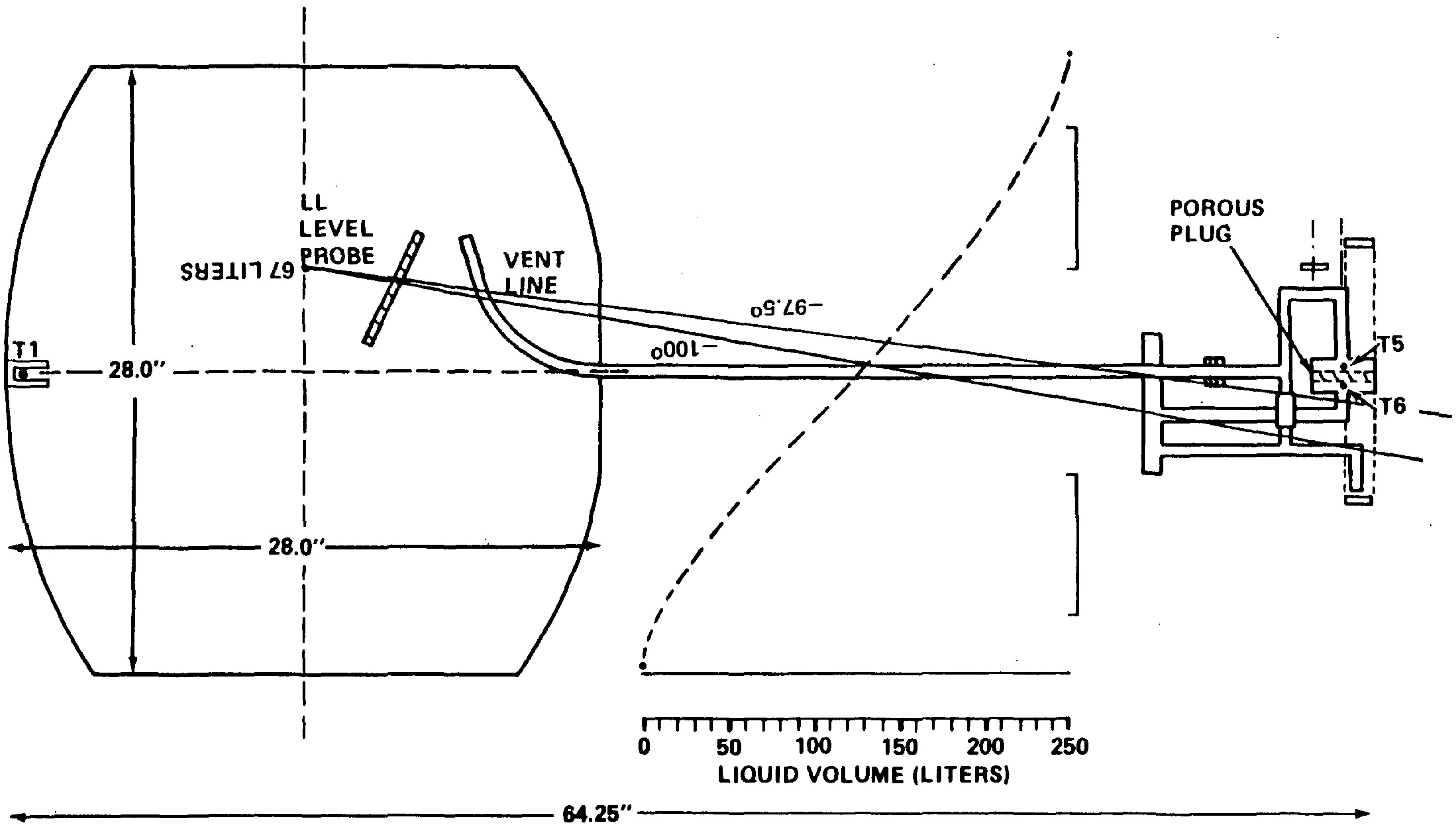

Figure 46b. Tilt angles and liquid levels, second tilt test, TPE VII.

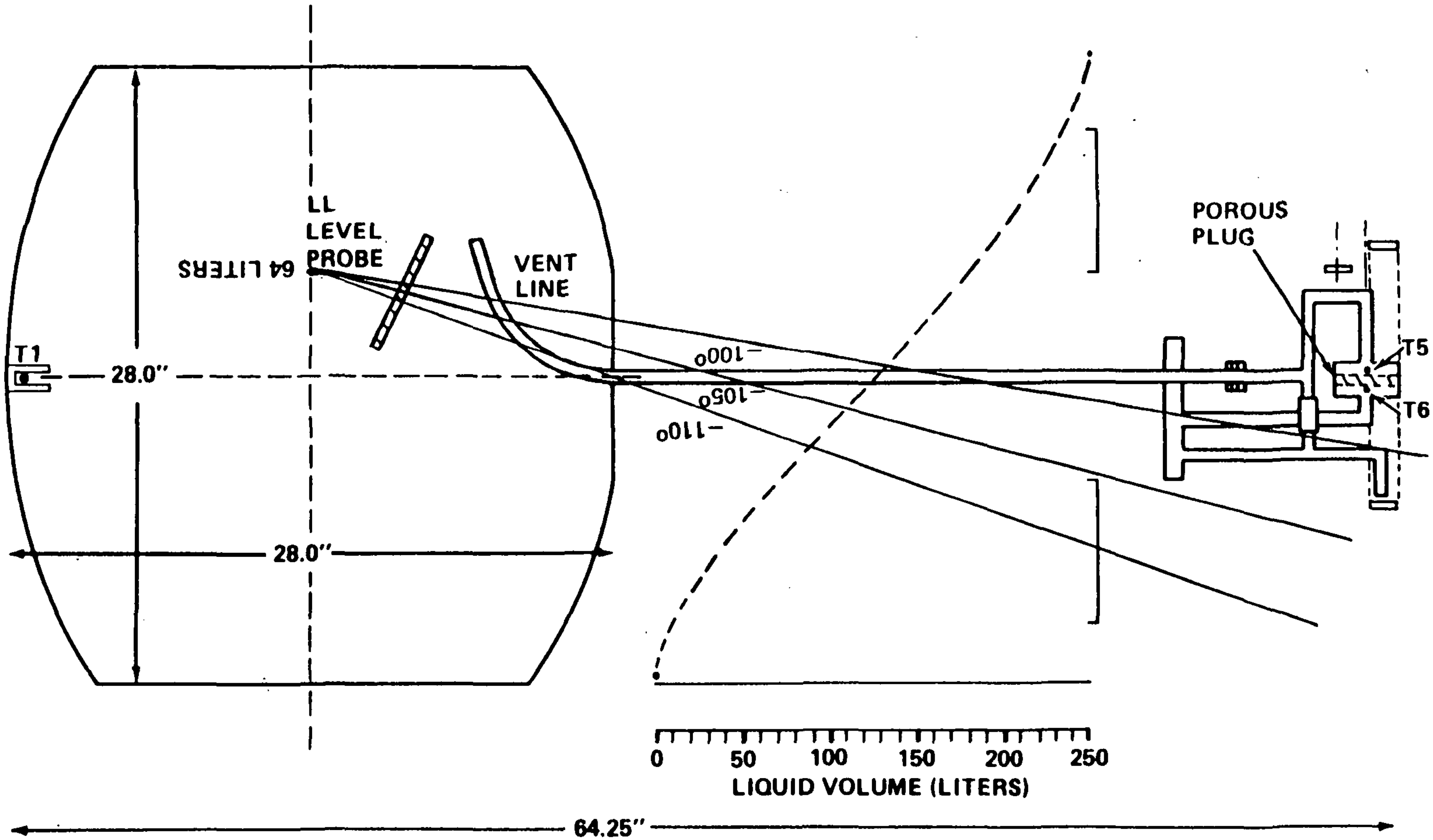

Figure 46c. Tilt angles and liquid levels, second tilt test, TPE VII.

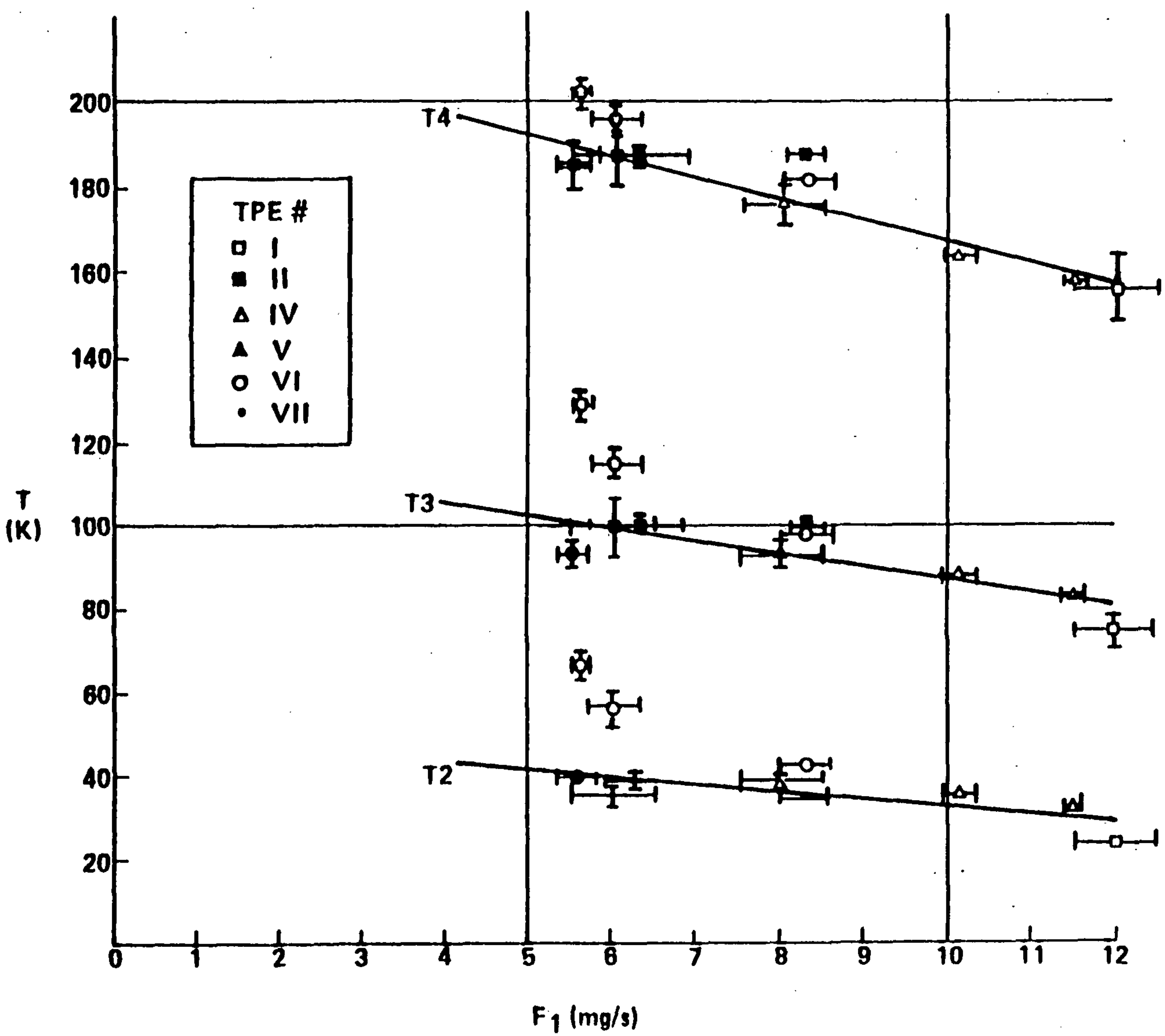

Figure 47. Dewar VCS temperature vs. mass flow rate, steady state.

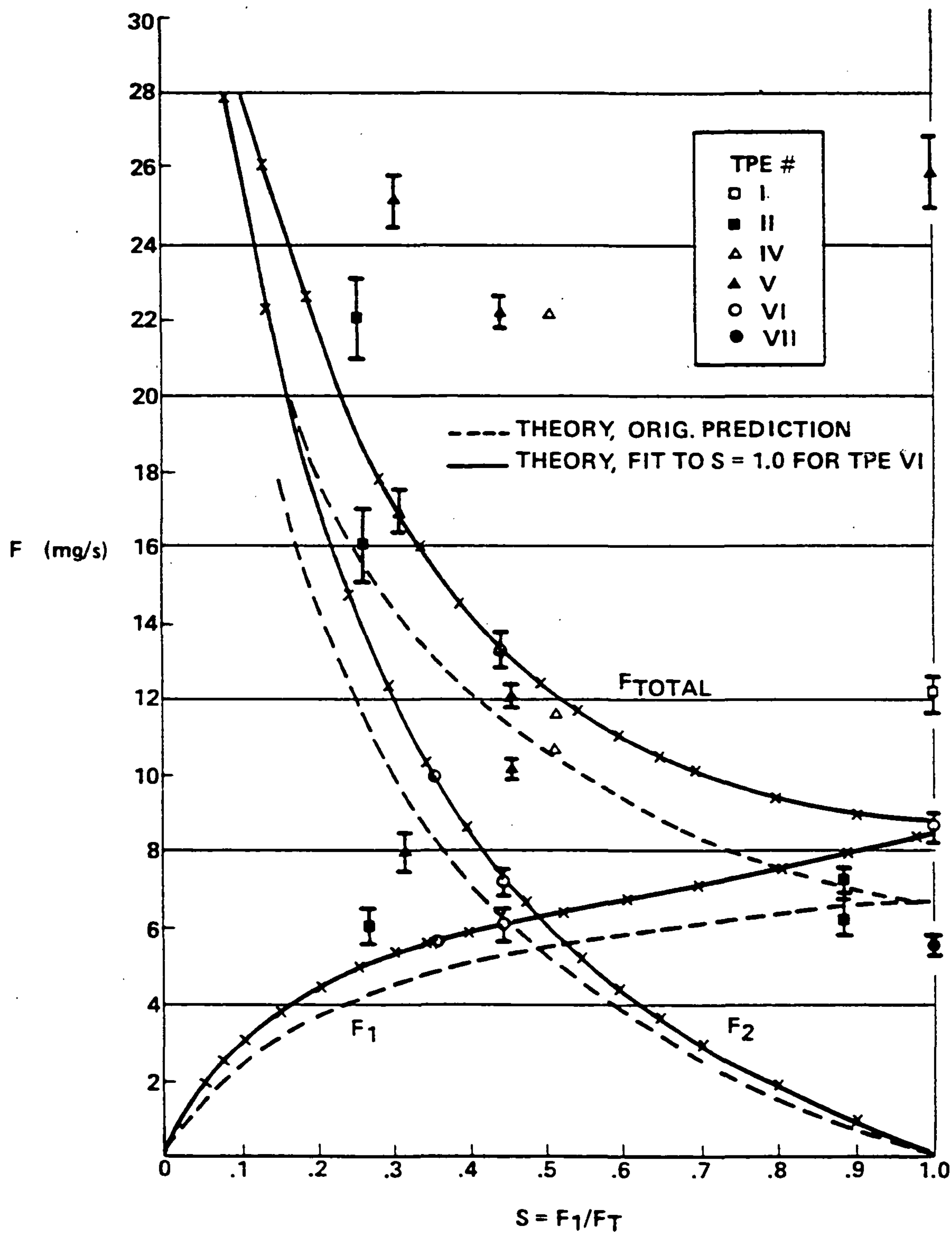

Figure 48. System mass flow rate vs. divided flow ratio, steady state.

APPROVAL

THERMAL PERFORMANCE EVALUATION OF THE INFRARED TELESCOPE DEWAR SUBSYSTEM

By

Eugene W. Urban

The information in this report has been reviewed for technical content. Review of any information concerning Department of Defense or nuclear energy activities or programs has been made by the MSFC Security Classification Officer. This work, in its entirety, has been determined to be unclassified.

A. J. DESSLER
Director, Space Science Laboratory

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